BOND STRENGTH OF GROUTED REINFORCING BARS

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ABSTRACT

The effects of hole preparation method, grout type, hole diameter, bar size, embedment length, cover, reinforcing bar deformation pattern, bar surface condition (epoxy coated or uncoated), orientation of the installed bar, and concrete strength on the bond strength of grouted reinforcing bars are described. Hole preparation methods, using a high-speed vacuum drill or a hand-held pneumatic hammer drill, and cleaning methods, using a fiber bottle brush with water, a fiber bottle brush without water, or compressed air only, are compared. Two capsule systems, two two-component grout systems, and two nonshrink grout systems are evaluated. Hole diameters range from $^3/_4$ to $1^1/_2$ in. for No. 5 bars; $1^1/_4$ in. diameter holes are used for No. 8 bars. Embedment lengths range from 4 to 12 in. for No. 5 bars and from 6 to 15 in. for No. 8 bars. $1^1/_2$ in. and 3 in. covers are used. Two deformation patterns bars are evaluated. Bar installations include vertical, sloped, and horizontal bars. Concrete strengths range from 2700 to 5900 psi. Test results are used to develop rational design and construction requirements. A standard test to establish the Strength Class of a grout for anchoring reinforcing bars is proposed. In addition, a test method currently in use by one state department of transportation as a technique for proof-testing grouted reinforcement in the field is evaluated.

The bond strength of grouted reinforcing bars is not highly sensitive to differences in the hole preparation or cleaning methods studied. Grouts that provide strong bond at the grout-concrete interface provide higher bond strengths than grouts that undergo failure at the grout-concrete interface. With the exception of bars anchored by capsule systems, the bond strength provided by grouts is not sensitive to hole diameter. Bond strength increases with increasing embedment length, cover, and bar size. The bond strength of grouted reinforcement is only slightly sensitive to reinforcing bar deformation pattern, and insensitive to the presence of epoxy coating. Vertically and horizontally anchored bars may exhibit different bond strengths, depending on the grout used. For the grouts tested, bond strength increases approximately with the square

root of the concrete compressive strength. The proposed standard test method for establishing the Strength Class of a grout is incorporated in a conservative, easy-to-use design procedure. The test method evaluated for proof-testing reinforcement is not recommended because the failure modes are often different and the strengths are higher than those obtained under more realistic loading conditions. A modification to the test method is suggested.

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CHAPTER 1
INTRODUCTION

Grouting reinforcement into holes drilled in existing structures is commonly specified in highway construction. The procedure is used to attach barriers, widen existing bridges, and repair damage (Stratton et al. 1977, 1978, 1982). In spite of its widespread use, little data exists on the bond strength of grouted reinforcement to concrete. This lack of data greatly limits the development of rational anchorage design procedures and increases the difficulty in establishing the true margin of safety and the economy of grouted bar installations. Current design methods often entail the use of proprietary design tables provided by grout manufacturers. These tables provide strength results that are based on highly confined pullout specimens. The strengths are then typically reduced by a factor of 4 to establish "allowable" anchorage strengths. As will be demonstrated in this report, the strength and mode of failure provided by highly confined specimens do not, in general, match those obtained by grouted bars loaded under realistic conditions.

Prior to the current study, there have been limited efforts to establish the strength of grouted reinforcement (Stowe 1974, Cannon et al. 1981). This earlier work has involved the anchorage of reinforcing bars in applications involving very high cover, such as used for concrete anchors. The use of high cover is not generally representative of highway bridge construction in which covers as low as $1\frac{1}{2}$ in. are used for grouted reinforcement. Thus, the previous work is not only limited, but provides generally unconservative values of strength for grouted bars with low amounts of cover. In addition, the previous work has used uncoated reinforcement, rather than the epoxy-coated reinforcement used in most transportation structures today. The effect of epoxy coating on the bond strength of grouted reinforcement is, thus, largely unknown.

The behavior and design of both cast-in-place and retrofit concrete anchors have been thoroughly studied at the University of Texas (Collins et al. 1989, Doerr and Klingner 1989, Cook and Klingner 1989, Cook et al. 1989, 1992). Although that research does not specifically address grouted reinforcing bars, it provides a wealth of information on the subject of anchorage to concrete.

The purpose of this study is to develop a pool of data on the bond strength of grouted reinforcing bars and to use that data to develop rational design and construction requirements. The experimental program addresses the effects of hole preparation method, grout type, hole diameter, bar size, embedment length, cover, reinforcing bar deformation pattern, bar surface condition (epoxy coated or uncoated), orientation of the installed bar, and concrete strength. In addition, a test method currently in use by one state department of transportation (Kentucky 1991) is evaluated as a technique for proof-testing grouted reinforcement in the field.

The following chapters describe the overall experimental program, evaluate the test results, present the design and construction recommendations, and evaluate the field test method. Appendix A of the report presents a proposed standard test method for evaluating grouts for anchoring reinforcing bars. This study provides design and construction guidance that will improve both the safety and the economy of grouted reinforcing bars.

CHAPTER 2

EXPERIMENTAL PROGRAM

The overall experimental program included 492 tests of grouted and cast-in-place reinforcing bars. The majority of the tests involved grouted reinforcement. The test specimens were cast in 23 groups (groups 1, 2, 4-24 – no tests for Group 3) consisting of 6 to 12 concrete specimens each. Each specimen contained 2 to 6 test bars. The key test parameters were hole preparation method, bonding method, hole diameter, bar size, embedment length, cover, deformation pattern, bar surface condition (epoxy coated or uncoated), orientation of the bar, and concrete strength. A field test method, similar to the method used by the State of Kentucky, was also evaluated (details in Chapter 5).

2.1 Test Specimen

A standard test specimen developed at the University of Kansas (Brettmann et al. 1984, 1986) was modified to provide realistic degrees of concrete confinement to match the behavior of grouted bars in transportation structures. The test specimen and the various bar installations used in this study are illustrated in Figs. 2.1a and 2.1b.

As shown in Fig. 2.1, the test specimen consisted of a block of concrete 24 in. long by 27 in. wide by 24 in. high. A typical test specimen contained 2 vertical or 2 sloped bars anchored on the upper surface (Fig. 2.1a) or 2 horizontal bars anchored on a vertical surface (Fig. 2.1b), one anchored near the upper surface and one anchored near the lower surface of the specimen. However, some specimens contained as many as 6 test bars. As constructed and tested, the failure of individual bars was unaffected by other bars in the test specimen. No. 5 and No. 8 bars were used in this study.

Most tests involved bars with 3 in. of cover; selected tests (in Groups 19 and 22) involved bars with $1^1/_2$ in. cover. Embedment lengths of 4, 6, 9, and 12 in. were used for No. 5 bars, while embedment lengths of 6, 9, 12, and 15 in. were used for No. 8 bars. The test bars extended 21 in. out from the face of the specimen.

Based on experience with narrower test specimens (Brettmann et al. 1984, 1986), auxiliary reinforcement was added parallel to the test bars to provide additional tensile capacity to the concrete (Fig. 2.1). Two No. 5 auxiliary bars were used for No. 5 test bars, while two No. 6 auxiliary bars were used for No. 8 test bars. Auxiliary bars had 2 in. of cover and were centered 6 in. on either side of the test bars. Some test specimens (Groups 1, 2, and some bars in Groups 21 and 24) did not contain auxiliary reinforcement. As will be discussed in Chapter 3, the presence of auxiliary reinforcement is not required in these test specimens and plays no measurable role in specimen behavior or strength. Test specimens were provided with two horizontal No. 8 bars to allow for lifting.

Tests were made on both cast-in-place and grouted bars; the majority of the tests involved grouted reinforcement. Both epoxy-coated and uncoated bars were evaluated. Epoxy-coated reinforcement was used in most of the tests, due to its wide application in transportation structures.

A number of hole diameters were evaluated in the study. Grouted No. 5 bars were anchored in holes with diameters of $^3/_4$, $^{13}/_{16}$, and $^7/_8$, and $1^1/_2$ in., while grouted No. 8 bars were anchored exclusively in holes with diameters of $1^1/_4$ in. Most tests involved holes with diameters $^1/_4$ in. larger than the bar diameter ($^7/_8$ in. and $1^1/_4$ in. for No. 5 and No. 8 bars, respectively).

The test specimens were cast in forms constructed using $^3/_4$ in. B-B plyform and 2 x 4 studs. The forms were coated with polyurethane to prevent water from being absorbed, and the joints were caulked to prevent leakage.

2.2 Materials

Reinforcing Steel.–ASTM A 615 (1990) Grade 60 No. 5, No. 6, and No. 8 bars were used for the tests. Bars with two deformation patterns, designated S and C, were tested, with the majority of the tests involving the C deformation pattern. Deformation pattern S consisted of ribs perpendicular to the axis of the bar, while deformation pattern C consisted of diagonal ribs inclined 60° with respect to the axis of the bar. Yield strengths and deformation properties are shown in Table 2.1. Epoxy coating, 3M Scotchkote 213, was commercially applied in accordance with ASTM A 775 (1991).

Concrete.–Air-entrained concrete was supplied by a local ready mix plant. Type I portland cement and $^3/_4$ in. nominal maximum size coarse aggregate were used. The coarse aggregate was crushed limestone and the fine aggregate was Kansas river sand. Water-cement ratios of 0.42 to 0.46 and air contents of 1.9 to 6.8 percent were used to produce concretes with nominal strengths of 2500 or 5000 psi. The majority of the tests were carried out with 5000 psi concrete. Mixture proportions are shown in Table 2.2. Concrete properties for individual specimen groups are given in Table 2.3.

Grout.–Six grouting materials were evaluated in the study. Two capsule systems (designated CPA, CPB), two two-component systems (TCA, TCB), and two nonshrink grouts (NSA, NSB) were evaluated in the study. CPA consisted of a vinyl ester resin system, and CPB consisted of a polyester resin system. TCA consisted of a vinyl ester resin system, while TCB consisted of an epoxy resin system. NSA and NSB consisted of nonmetallic cementitious nonshrink grout systems. The study placed major emphasis on four of the grouting systems, CPA, TCA, TCB and NSA. Additional details on the grouting materials are provided in Table 2.4.

2.3 Fabrication Procedure

Fabrication of the test specimens involved placement of the auxiliary reinforcement and lifting bars, along with cast-in-place bars, if included in the test group. The cast-in-place test bars were rigidly supported from the outside of the form. The balance of the reinforcement was firmly tied in place on chairs attached to the forming material using tie wire.

Beginning with Group 8, the order in which the specimens were cast was selected to reduce the effects of systematic differences in the concrete properties from different portions of a batch. Bars with the same parameters were dispersed throughout a test group and did not occupy the same casting positions in any two test groups.

Concrete was placed in two lifts. The first lift was placed in all specimens in a group before any specimen received a second lift. Each lift was vibrated with a $1^1/_2$ in. electric vibrator at four evenly spaced points. Following placement and finishing, the specimens were coated with curing compound and covered with plastic. Standard 6 x 12 in. test cylinders were cast in steel molds and cured in the same manner as the test specimens. Forms were stripped after 6 or 7 days (concrete strengths in excess of 3000 psi).

Two types of drills, a high-speed, hydraulic, truck-mounted vacuum drill and a hand-held electric rotary hammer drill, were used to place holes in the specimens. The high-speed vacuum drill had been developed by the Kansas Department of Transportation as a means to add shear reinforcement to bridges (Stratton et al. 1977, 1978, 1982). The drill was originally configured to place 1 in. diameter holes (to receive No. 6 reinforcing bars) to a depth of 7 ft. The drill advanced at 2 ft per min. New shafts and drill bits were made by H/S Products, Inc. of Wichita, Kansas to make $^7/_8$ in. and $1\,^1/_4$ in. diameter holes for the No. 5 and No. 8 bars used in this study. Some breakage occurred with the new drill bits. However, it was found that continuous drilling (without rapid starting and stopping) provided an improved life and satisfactory performance of the drill bits.

Most of the test specimens were prepared using a Hilti model TE-92 hand-held rotary drill hammer. Drill bits with diameters of $^3/_4$, $^{13}/_{16}$, $^7/_8$, $1\,^1/_4$, and $1^1/_2$ in. were provided with the drill. The drill was easy to use and cut rapidly through the concrete.

To accommodate the truck-mounted, high-speed vacuum drill, the drilling face of the test specimens had to be tilted approximately 25° from the vertical. For the hand-held drill, holes were drilled vertically for both vertical and horizontal test bars. The holes for the bars in Group 24 that were oriented with slopes of 1:3 or 1:6 were drilled with the drilling face oriented in a horizontal direction. A shop vacuum cleaner was used in conjunction with the hand-held drill to remove the cutting debris at the top of the hole.

Four cleaning methods were evaluated in the study: 1) using the truck mounted vacuum drill, with no additional hole preparation (V); 2) vacuuming the bottom of the hole with a shop vacuum cleaner with a $^1/_2$ in. outside diameter nozzle, followed by thorough scrubbing with a fiber bottle brush and water and blowing out the hole with compressed air (BW); 3) vacuuming with the shop vacuum cleaner, brushing with the fiber bottle brush (no water) and blowing out the hole with compressed air (BA); and 4) vacuuming the hole with the shop vacuum cleaner and blowing out the hole with compressed air (A). The air compressor was fitted with an in-line filter to remove oil and water from the compressed air. Methods BW, BA and A were used for holes made with the hand-held drill. Method V is used by the Kansas Department of Transportation for special reinforcing bar placements (Stratton et al. 1977, 1978, 1982). Method BW represents the current Kansas Department of Transportation specifications (KDOT 1990) for anchoring grouted reinforcement.

Grouts and reinforcing bars were placed according to the manufacturer's instructions (Table 2.4). A manual dispenser provided by Hilti Corporation was used to place TCA, which was prepackaged for automatic proportioning during installation. TCB was batched by volume (2 parts A to 1 part B) and mixed for 3 min., according to the manufacturer's instructions. In the plastic state, TCA had the consistency of tooth paste and set rapidly, while TCB had the consistency of honey and set slowly. As a result, TCA could be used in both vertical and horizontal holes, while TCB, without the addition of a filler or special provision to prevent leakage in horizontal holes, could be used only in vertical holes.

The capsule systems, CPA and CPB, contained two components sealed in glass tubes. The individual capsules were placed in holes and the reinforcing bar, with a chisel point (45° angle) was attached to the hammer drill with a special drive socket (a Hilti DE-F reinforcing bar adapter) and drilled to the bottom of the hole. Following manufacturers recommendations, rotation was stopped, in most cases, when the bar hit the bottom of the hole. The effects of extra rotation and the use of multiple capsules were studied (Group 11) and are described later in this report.

The nonshrink grouts were mixed until uniform. NSA and NSB were combined with 1.5 and 2.55 gallons of water, respectively, per 55 lb bag to produce grout with a fluid consistency.

To avoid air pockets and insure complete filling of a hole, grouts were poured down one side of the hole and placement was completed without interruption. Bars were inserted by hand after placement of the two-component and nonshrink grouts. Following insertion of the reinforcing bar, exposed surfaces were sealed with duct tape. Grouts were cured for a minimum of three days.

2.4 Test Procedures

Tests were carried out at nominal concrete strengths of 2500 or 5000 psi, with the majority of the tests carried out at 5000 psi. Specimens were tested at ages ranging from 5 to 78 days, as shown in Table 2.3. The test system, illustrated in Fig. 2. 2, was used to apply load at approximately 3 kips per minute for No. 5 bars and 6 kips per minute for No. 8 bars. During a test, the specimens were anchored to the structural floor by a wide-flange section and two tie-down rods. Load was applied to the test bar by two 60-ton hollow-core hydraulic jacks powered by an Amsler hydraulic testing machine through two 1 in. diameter load rods instrumented as load cells. As shown in Fig. 2.2, the hydraulic jacks exerted a pulling force on two yokes (one above and one below the test bar); the test bar was loaded in tension by the yokes through a wedge-grip assembly. The tensile force on the bar was counteracted by a compressive force imposed on the concrete specimen through a 4-in. deep steel bearing plate. The edge of the plate was located $4\,^1/_2$ in. below the center of the test bars, except for specimens labeled NTR in Group 24 for which the spacing was increased to 12 in. to evaluate the effects of changes in degree of confinement provided to the test bar based on the proximity of the bearing plate. Loaded-end slip was measured using two spring-loaded linear variable differential transformers (LVDTs) attached to an aluminum block mounted on the test bar 4 in. from the face of the concrete. The load rods and the LVDTs were connected to a Hewlett-Packard data acquisition system that recorded load and bar slip at 1 sec intervals.

2.5 Results and Observations

Test variables and bond strengths are listed in Table 2.5. Details on bar size, bar orientation and deformation pattern, bar surface condition, embedment length, hole diameter, hole preparation method, anchorage method (type of grout plus cast-in-place bars), cover, concrete strength, bond strength, and failure mode are provided for each specimen.

Failure modes.–The test specimens exhibited 6 failure modes, identified as S, IGC, Cone, T, Pullout, and IGR. In many cases, failure involved a combination of these modes.

Most of the test specimens exhibited a splitting (S) failure (tensile cracks in the concrete parallel to the reinforcing bar) or a failure at the interface between the grout and the concrete (IGC). These failure modes often occurred in conjunction with the formation of a small, shallow angle concrete cone surrounding the reinforcing bar on the face of the specimen (Cone). Some specimens exhibited a tensile (T) failure mode in which the concrete test specimen failed due to tensile/flexural cracks perpendicular to the direction of loading, while some specimens exhibited no sign of failure other than bar pullout. Unless the failure mode is also identified as IGC, the S, T, and Cone failure modes listed in Table 2.5 were accompanied by a failure at the interface between the grout and the reinforcing bar (IGR) (or concrete-reinforcing bar interface, in the case of cast-in-place specimens).

Splitting failure, the type of failure exhibited by most cast-in-place reinforcing bars (Clark 1949, Menzel 1952, Ferguson and Thompson 1962, Losberg and Olsson 1979, Johnston and Zia 1982, Hester et al. 1993) was the primary mode of failure for bars anchored with Capsule B (CPB), Two-component grout B (TCB), Nonshrink grout A (NSA), Nonshrink grout B (NSB), and No. 8 bars anchored with Capsule A (CPA). For cast-in-place bars, splitting failures are governed primarily by the strength of the concrete and any confining reinforcement, such as stirrups or ties (Orangun et al. 1975, 1977, Darwin et al. 1992a, 1992b) (confining reinforcement was not used in this study). For grouted bars, a splitting failure indicates a close interaction between the grout and the surrounding concrete. Splitting failures usually involve a crack emanating from the bar, perpendicular to the cover, and additional cracks around the periphery of the bar, as illustrated in Figs. 2.3 and 2.4. Splitting failures were usually accompanied by failure at the reinforcing bar-grout interface.

Failure at the interface between the grout and the concrete (Figs. 2.5 and 2.6) indicates a lack of bond between the two materials. This type of failure generally results in a lower anchorage strength than a splitting failure. IGC was the primary mode of failure for bars anchored with Two-component grout A (TCA). The IGC failures shown in Figs. 2.5 and 2.6 were also accompanied by the formation of a shallow concrete cone.

A combined splitting (S) and tensile (T) failure is illustrated in Fig. 2.7.

Pullout was the primary mode of failure for No. 5 bars anchored with CPA.

The failure modes obtained for bars in Group 24, for which the steel bearing plate was moved from $4^1/_2$ in. below the center of the test bars to 12 in. below the center of the test bars, showed no significant differences from those obtained in the balance of the tests, indicating little difference in the degree of confinement provided to the bars based on the two bearing plate positions.

Load-Slip Curves.–Representative load-loaded end slip curves are shown in Figs. 2.8-2.16 for No. 5 bars and 2.17-2.22 for No. 8 bars. Figs. 2.8-2.11 present the curves for the cast-in-place uncoated, cast-in-place coated, TCA grouted, and TCB grouted bars, respectively, in Group 17 with embedment lengths of 4, 6, 9, and 12 in. Fig. 2.12 shows the curve for CPA grouted No. 5 bars with ℓ_e = 4, 6, 9, and 12 in. Figs. 2.13-2.16 show selected load-slip curves for CPA, CPB, NSA, and NSB grouted No. 5 bars with ℓ_e = 6 in. from Groups 4-6. Figs. 2.17-2.20 show load-slip curves for cast-in-place uncoated, cast-in-place coated, TCA grouted, and TCB grouted No. 8 bars, respectively, with ℓ_e = 6, 9, 12, and 15 in. Fig. 2.21 shows curves for NSA grouted horizontal top-cast No. 8 bars with ℓ_e = 6, 9, and 12 in. bars from Group 18. Fig. 2.22 shows the curves for CPA grouted horizontal top-cast No. 8 bars with ℓ_e = 6, 9, 12, and 15 in. from Group 20.

The figures illustrate that the initial stiffness (slope) of the load-slip curves is independent of embedment length. With the exception of the CPA grouted bars illustrated in Fig. 2.12, an increase in embedment length results in an increase in strength. Most bars exhibit a rapid increase in bond force with increasing slip, reaching the peak force at a loaded-end slip of less than 0.1 in. The initial stiffness of the load-slip curves appears to be very similar for a given bar size, independent of the anchorage method. Exceptions to the last two observations are provided by 1) the TCA grouted bars (Figs. 2.10 and 2.19), which uniformly exhibit a lower initial stiffness, as well as a lower strength, than bars anchored with other grouts, and peak loads at slips in excess of 0.1 in.; and 2) No. 5 bars with embedment lengths sufficient to develop a bond force in excess of 20 kips, at which point the bars begin to yield, resulting in significantly increased loaded end slips. As shown in Figs. 2.8 and 2.9, for loads above 20 kips, the load-slip curves take on the general shape of a stress-strain curve at and above yielding. Another exception is observed for the curves for the CPA grouted No. 8 bars (Fig. 2.22) which exhibit a lower stiffness than the other No. 8 bars because the grout (limited by the amount of grout in a single capsule) fills only about 8 in. of the hole. In most cases, the curves drop off very rapidly once the peak force is attained. In some instances (Figs. 2.8, 2.9, 2.17, 2.18, and 2.20), the load-slip curves drop off more slowly.

Some curves, such as shown in Figs. 2.8 and 2.9, contain a region near the peak load in which the curve rises vertically. This occurs when a cone of concrete pulls off the front of the specimen prior to failure. Although slip is continuing, the relative slip between the bar and the points of contact for the LVDT's is zero.

A comparison of Figs. 2.12 and 2.13 shows that the CPA grouted bars exhibit a slightly higher stiffness and significantly greater strength when the manufacturer's recommended hole diameter of $^{13}/_{16}$ in. is used (Fig. 2.13), rather than $^{7}/_{8}$ in. (Fig. 2.12).

A comparison of the curves shown for NSA and NSB grouted No. 5 bars in Figs. 2.15 and 2.16 shows little difference in behavior whether $^{7}/_{8}$ in. or $1^{1}/_{2}$ in. diameter holes are used.

The test results are discussed in greater detail in Chapter 3.

CHAPTER 3

EVALUATION OF EXPERIMENTAL RESULTS

The principal goals of this project are to develop basic data on the strength of grouted reinforcing bars and to formulate anchorage provisions for use in design. The study is also aimed at evaluating hole preparation methods and representative grouting systems used.

Test results are compared primarily on the basis of bond strength (force), which, observations show, depends on concrete strength. To account for differences in concrete strength, bond strengths are normalized with respect to a nominal concrete strength of 5000 psi using the assumption that, within the concrete strength range used, bond forces are proportional to the square root of the concrete compressive strength. Thus, experimental bond strengths are multiplied by $(5000/f'_c)^{1/2}$ to obtain modified values that are used for comparison and analysis. Both original and modified values of bond strength are summarized in Table 2.5.

The following sections cover the effects of hole diameter, bar surface condition, hole preparation method bonding method, embedment length, bar diameter, cover, bar orientation, concrete strength and the presence of parallel tensile reinforcement.

3.1 Hole Diameter, Bar Surface Condition, Hole Preparation Method and Bonding Method

Initial efforts in this study were aimed at defining the effects of hole preparation method and grouting material. Groups 1, 2, 4, 5, and 6, for No. 5 bars, and Groups 8, 9, and 10, for No. 8 bars, were used to obtain this information, which was used, in turn, to determine the test parameters to be evaluated as the study progressed. In these groups, vertically anchored No. 5 and No. 8 bars were grouted with embedment lengths of 6 and 9 in., respectively. Groups 1 and 2 used uncoated bars in conjunction with the grouting materials. Groups 4, 5, and 6 used both uncoated and epoxy-coated bars with the grouting materials. Groups 8, 9, and 10 used only coated bars with the grouting materials. All eight groups included coated and uncoated cast-in-place bars.

Groups 1 and 2.–The tests in Groups 1 and 2 compared the strengths of No. 5 bars anchored with Capsule A (CPA), Nonshrink grout A (NSA), and Two-component grout A (TCA) in small holes (with diameters of $^{13}/_{16}$ in., $^{7}/_{8}$ in., and $^{3}/_{4}$ in., respectively, as recommended by the manufacturers) and NSA and TCA grout in large holes ($1^{1}/_{2}$ in. diameter). All holes were drilled using the hand-held rotary hammer drill. Three cleaning methods, brush with water (BW), brush with air (BA), and air (A), were used.

Overall, the results, presented in Table 2.5, illustrate that, for the methods tested, bond strength is not especially sensitive to the hole cleaning method. For the small holes, bond strengths are highest for holes cleaned with the BW method. Holes cleaned with the BA or A method provide lower, approximately equal, strengths. For CPA, the average strengths for BW, BA, and A, respectively, are 18.36, 16.08, and 17.22 kips. For NSA, the bond strengths are 16.74, 15.05, and 14.94 kips. For TCA, the strengths are 14.69, 10.12, and 9.95 kips. These differences in strength appear to be significant only for TCA. The uncoated and coated cast-in-place bars have average strengths of 14.37 and 14.44 kips, respectively.

For the large holes, differences in cleaning method also appear to have little effect on bond strength of bars. For these tests, the BA method consistently provides a higher strength than the A method, which provides a higher strength than the BW method. For NSA, the strengths for BA, A, and BW are 16.96, 15.03, and 14.47 kips, respectively. For TCA, the strengths are 11.42, 11.33, and 9.04 kips, respectively. CPA was not used for large holes because of the amount of grout in the capsule and the aggregate particles in CPA are selected based on bar size and hole diameter.

A comparison of the strengths given above for bars anchored with NSA and TCA grouts in small and large holes indicates no discernible effect of hole diameter on bond strength.

Of the three grouts, CPA provides the highest strength, followed by NSA and TCA for bars anchored in small holes. NSA provides a higher strength than TCA for bars anchored in large holes. The difference in strength between CPA and NSA grout does not appear to be significant. However, both grouts provide significantly higher strengths than TCA. The lower strength TCA grouted bars uniformly exhibited failure at the interface between the grout and the concrete (IGC), while the higher strength CPA and NSA grouted bars exhibited a splitting (S) failure. The IGC failure of the rapid setting TCA grout may be due to limited wetting of the concrete surface.

Groups 4, 5, and 6.–Groups 4, 5, and 6 were used to expand the investigations initiated in Groups 1 and 2 to include coated reinforcing bars and all six of the grouts evaluated in the study. In these groups, both uncoated and coated cast-in-place bars provided higher strengths than the grouted bars. The BW cleaning method was used exclusively, except for a specific study of NSA bars in large holes, in which the BW, BA, and A methods were evaluated.

One bar was tested in each of the three groups for each combination of variables. Only two usable tests were obtained for the epoxy-coated NSA (E-NSA) grouted bars in small holes. To aid in the comparisons of test results, the statistical significance of differences in average bond strengths are evaluated using hypothesis testing (Hogg and Ledolter 1992). Both the student t-test and the more stringent "z-test" are used. For the z-test, estimates of the standard deviation of bond strength are obtained by treating groups of grouted bars that exhibit splitting failure as individual samples from a single larger population. TCA grouted bars, which generally exhibit IGC failures, are treated as a second population. The calculations of variance and standard deviation for the bars in Groups 4, 5, and 6 are presented in Table 3.1 and the student t-test and z-test results are presented in Tables 3.2 and 3.3, respectively.

> A summary of how to use these comparisons follows: The comparisons made in Tables 3.2 and 3.3, and later in Tables 3.5, 3.6 and 3.8, provide guidance as to whether the mean bond strengths for different sets of test variables represent the same strengths (with differences due only to scatter in the data) or different strengths. A decision can be made by testing the "null hypothesis", H_o, that the measured mean strengths, $\bar{X}_1$ and $\bar{X}_2$ represent populations with mean strengths, μ_1 and μ_2, that are equal. The null hypothesis ($\mu_1 = \mu_2$) cannot be rejected if $\bar{X}_1$ and $\bar{X}_2$ are not too far apart. What is "not too far apart" depends on the standard deviations of the test results and the "level of significance," α. The level of significance

represents the probability of rejecting the null hypothesis ($\mu_1 = \mu_2$) when H_o is true. Increasing the value of α makes it easier to reject H_o and conclude that $\overline{X}_1$ and $\overline{X}_2$ represent populations with real differences in the μ_1 and μ_2. Testing H_o ($\mu_1 = \mu_2$) against the alternate hypothesis, H_1 ($\mu_1 \neq \mu_2$), is known as a two-sided test, since H_o is really being compared against two alternate hypotheses, $\mu_1 > \mu_2$ and $\mu_1 < \mu_2$, each of which is considered with a level of significance $\alpha/2$. For this analysis, values of $\alpha/2$ of 0.1, 0.05, 0.025 and 0.01 are used. If the null hypothesis is rejected, the lower the value of $\alpha/2$ at which this occurs, the greater the probability that $\mu_1 \neq \mu_2$.

The student t-test is used most often for hypothesis testing in situations where only small samples are available and the true population standard deviations are not known. The results of hypothesis testing using the student t-test are shown in Table 3.2. If H_o is not rejected ("NO" in Table 3.2), then the mean strengths being compared may be treated as being not significantly different at the particular $\alpha/2$. If H_o is rejected ("YES"), the mean strengths may be treated as being significantly different.

Although these comparisons deal with small samples, use of the student t-test alone has some drawbacks. Principal among these is the fact that the measured standard deviations, s_1 and s_2 are random variables themselves. Thus, as illustrated in Table 3.2, the values of s can differ markedly. As a result, two means, $\overline{X}_1$ and $\overline{X}_2$, may be very close and still be treated as being significantly different, if s_1 and s_2 happen to be small. Likewise, $\overline{X}_1$ and $\overline{X}_2$ may be far apart and be treated as not significantly different, if s_1 and/or s_2 are large.

To help remove some of the inconsistencies caused by variations in s, hypothesis testing is also carried out in this study using the "z-test." In this case, specimens that exhibit similar modes of failure are treated as belonging to the same population for which a close estimate of the population standard derivation, σ, can be obtained. This calculation is carried out in Table 3.1 and the results of hypothesis testing using the z-test are shown in Table 3.3.

Interpretation of the results of hypothesis testing is ultimately subjective. However, the process of hypothesis testing provides a useful basis for comparing data, such as is required in this study. The reader is referred to a standard text on statistics for additional discussion.

Bar Surface Condition.–To determine the effect of bar surface condition, uncoated and epoxy-coated bars were anchored with TCA and NSA grouts in both small and large holes. All of the TCA anchored bars exhibited an IGC failure and, thus, were not sensitive to the surface condition of the bars. The NSA grouted bars exhibited a splitting failure, followed by failure at the interface between the grout and the reinforcing bar (IGR). For small holes, the uncoated bars provide a higher average bond force, 15.08 kips, than the coated bars, 13.11 kips. However, for large holes, the coated bars provide a higher strength, 14.94 kips, than the uncoated bars, 14.20 kips. As shown in Tables 3.2 and 3.3, these differences in strength are not statistically significant. Overall, the presence or absence of epoxy coating appears to play little role in the bond strength of grouted reinforcement.

Hole Diameter.–Hole diameter also appears to have little effect on the strength of most grouted bars. For bars anchored in both small and large holes (NSA-coated and uncoated, NSB-coated, TCA-coated and uncoated, TCB-coated), the small holes ($^7/_8$ in. diameter) provide a higher average strength in half of the cases, while the large holes ($1\,^1/_2$ in. diameter) provide a higher average strength in the other half. In no case is the difference in bond force significant (Tables 3.2 and 3.3). These comparisons do not include capsules, since capsules are not meant for use in large holes. However, small differences in hole diameter can effect the strength of bars anchored with capsules (see Section 3.3).

Grout Material.–Two levels of strength were provided by the six grouts in Groups 4, 5, and 6, with NSA, NSB, and TCB providing significantly higher strengths than CPA, CPB, and TCA. The relative strengths differ somewhat from the results obtained for Groups 1 and 2, in which CPA provides the highest overall strength. As before, the TCA grouted bars exhibited an IGC failure, while the other grouts exhibited an S failure. For Groups 4, 5, and 6, TCB provides the highest average strength, 15.81 kips, and CPB provides the lowest average strength, 9.7 kips.

The lack of consistency in the strength provided by CPA and the apparent low strength of CPB raised some concern as to the effect of variations in concrete strength in individual test specimens. Although all concrete blocks within a group were cast from the same truck, there can be differences in concrete quality as the concrete is discharged. The effects of differences in concrete strength became very clear in Group 7 (Table 2.5). In that group, the weakest bond strengths were recorded for two bars in the same concrete block, while the highest strengths were recorded for two bars in another concrete block. As a result, Group 7 specimens are not used in the current analysis. In all groups following Group 7, bars were placed so as to minimize the effects of differences in concrete properties for blocks cast at different points during the discharge of the ready-mix truck.

Hole Cleaning Method.–The BW, BA, and A cleaning methods were evaluated using NSA grouted bars in $1\,^{1}/_{2}$ in. diameter holes. As for the bars grouted in the large holes in Groups 1 and 2, the BW cleaning method provides a lower strength than the BA and A methods (average strengths = 14.20, 15.34, and 15.50 kips, respectively). However, these differences are not statistically significant (Tables 3.2 and 3.3).

Groups 8, 9, and 10.– Groups 8, 9, and 10 were used to expand the study to consider larger bars and to help tie down the effects of hole preparation method on bond strength. No. 8 bars were anchored in holes prepared with the high-speed vacuum drill (cleaning method V) and the hand-held rotary hammer drill (cleaning methods BW, BA, A). Epoxy-coated bars were grouted in $1\,^{1}/_{4}$ in. diameter holes using CPA, NSA, TCA, and TCB, while both coated and uncoated bars were cast-in-place. As with Groups 4, 5, and 6, mean bond strengths in Groups 8, 9, and 10 (Table 3.4) are compared using both the student t-test (Table 3.5) and the z-test (Table 3.6).

Hole cleaning method and grout material.–Based on the student t-test (Table 3.5) with a level of significance, $\alpha/2$, of 0.025, there are few significant differences in bond strength for bars anchored with the CPA, NSA, and TCB grouts in holes prepared using any of the preparation methods (average bond forces range from 23.21 to 28.23 kips). The differences involve bars anchored with CPA grout, which consistently provide the highest strength (CPA anchored bars in BW, BA and A holes are also stronger than the cast-in-place bars). Significant differences are noted only for NSA/BA versus CPA/BA, and NSA/A and TCB/A versus CPA/A. Also, based on the student t-test at $\alpha/2 = 0.025$, there are no significant differences between the bond strengths of CPA, NSA and TCB grouted bars and the bond strength of TCA-grouted bars in vacuum drilled holes, 23.42 kips. There are, however, significant differences between the strength of these bars and the strength of TCA grouted bars in holes prepared using the BW, BA, and A cleaning methods, 16.63, 14.61, and 16.48 kips, respectively.

As shown in Table 2.5, a splitting (S) failure occurred in all cases for bars anchored with CPA, NSA, and TCB in holes prepared using all four methods and in all cases for bars anchored with TCA in holes prepared using the vacuum drill. However, IGC failures occurred in one, two, and all three specimens for TCA grouted bars prepared using the BW, BA, and A cleaning methods, respectively.

The evaluations provided by the z-test (Table 3.6) generally match those provided by the t-test. However, for $\alpha/2 = 0.25$, the z-test indicates that the higher strength provided by CPA/A is not significant compared to TCB/A, but that CPA/BA is significantly stronger than TCB/BA.

Group 11.–Group 11 specimens are used to 1) evaluate the effects of the number of capsules and extra rotations in placing reinforcing bars anchored with CPA and 2) compare V and BA hole preparation methods for No. 5 bars anchored with TCA. The statistical data and hypothesis testing are summarized in Tables 3.7 and 3.8, respectively.

Capsule anchoring method.–As shown in Table 2.5, the average strengths of No. 5 bars in Group 11 anchored with CPA show little sensitivity to the number of capsules or the number of rotations of the reinforcing bar during the anchoring process. Bars anchored using one or two capsules with a standard number of rotations (drill stops when bar hits the bottom of the hole) or extra rotations (an extra 15 sec of drill operation after the bar strikes the bottom of the hole) exhibit average bond strengths ranging from 13.22 to 15.40 kips. Bond strength increases in the following order: one capsule with a standard number of rotations (13.22 kips), two capsules with a standard number of rotations (14.22 kips), two capsules with extra rotations (14.31 kips), one capsule with extra rotations (15.40 kips). As shown in Table 3.8, these differences are not statistically significant (note: for $\alpha/2 \geq 0.05$, H_o is rejected for one capsule with the standard number of rotations compared to one capsule with extra rotations).

Hole preparation method.–A comparison of bond strengths obtained for TCA-grouted bars in holes prepared with 1) the high-speed vacuum drill (V) and 2) the rotary hammer drill and BA cleaning method indicates that the vacuum drill provides the higher strength, 11.08 kips versus 10.00 kips. As shown in Table 3.8, this difference is not statistically significant. However, the strength provided by TCA is significantly lower than provided by CPA for the bars in this group.

Summary.–Based on the analyses of the hole preparation methods used for the bars in Groups 1, 2, 4-6, and 8-11, the brush and air, BA, method was selected for the balance of the study and is recommended as the new standard of practice. With the exception of bars anchored with TCA grout, the other three methods do not appear to offer any strength advantages over the BA method. The higher strength provided for the TCA-grouted bars in holes prepared using the vacuum drill (V) is not a strong enough justification to require the V method for all applications. The BA method was selected over the current Kansas standard BW method (KDOT 1990) because it entails less effort. The BA method was selected over the A method because it represents a reasonable, yet higher, level of care than the A method and because of concern that the A method could easily degrade to a total lack of hole cleaning in the field.

3.2 Embedment Length, Bar Diameter, and Cover

A major focus of this study is to determine the effects of the key structural parameters, embedment length, bar diameter, and cover, on the bond strength of grouted reinforcing bars. It is generally acknowledged that the bond strength of cast-in-place reinforcing bars decreases as the cover decreases (Orangun et al. 1975, 1977, Darwin et al. 1992a, 1992b). The majority of the tests in the current study were carried out with 3 in. cover, the minimum recommended for grouted reinforcing bars in most bridge installations (ACI Committee 345 1992). A small number of tests were carried out with $1^1/_2$ in. cover. Recommended design procedures, presented later in this report, are based on the combined results for tests with different development lengths, covers, and bar diameters.

The comparisons that follow are based on grouted bars placed in holes prepared using the BA cleaning method. Equations of the best fit lines used for these comparisons (Figs. 3.1-3.14, 4.1, 4.2, 5.2) are given in Appendix B.

Embedment length.–The effect of embedment length, ℓ_e, on the modified bond strength, T_e, of vertically anchored No. 5 and No. 8 bars is illustrated in Figs. 3.1 and 3.2, respectively. Embedment lengths of 4, 6, 9, and 12 in. are used for No. 5 bars. Embedment lengths of 6, 9, 12, and 15 in. are used for No. 8 bars. Fig. 3.1 presents the combined results for Groups 11, 15-17, and 22; while Fig. 3.2 presents the combined results for Groups 8-10 and 12-14. The figures show the modified bond strengths and the best fit lines for uncoated and coated cast-in-place bars and epoxy-coated TCA and TCB grouted bars. The data in Fig. 3.2 and most of the data in Fig. 3.1 were obtained using C-pattern reinforcing bars. Fig. 3.1 also includes data for S-pattern cast-in-place coated and TCB grouted No. 5 bars.

The results illustrated in Figs. 3.1 and 3.2 match the observations made in Section 3.1. Overall, uncoated cast-in-place bars provide the highest strength, followed by coated cast-in-place bars, bars anchored with TCB grout, and, finally, bars anchored with TCA grout.

For the No. 5 bars (Fig. 3.1), the uncoated (denoted by M for mill scale) and epoxy-coated (E) cast-in-place (CIP) bars exhibit similar strengths for ℓ_e = 9-12 in. The coated bars exhibit lower strengths than the uncoated cast-in-place bars for ℓ_e < 9 in. length. For the No. 8 bars (Fig. 3.2), the uncoated cast-in-place bars are significantly stronger than the coated cast-in-place bars for all development lengths. Based on best-fit lines for C-pattern bars, the coated/uncoated bar strength ratio ranges from 0.90 to 1.06 for No. 5 bars and from 0.86 to 0.91 for No. 8 bars. The greater sensitivity of the larger cast-in-place bars to the epoxy coating matches the results obtained in earlier studies (Choi et al. 1990, 1991).

For both No. 5 and No. 8 bars, the bond strength of the TCB anchored bars is very close to the strength of the cast-in-place epoxy-coated (E-CIP) bars. The two anchorage methods produce nearly identical strengths at 4 and 6 in. for No. 5 bars, and at 6 in. for No. 8 bars. At higher embedment lengths, the cast-in-place epoxy-coated bars exhibit increasingly higher strength. However, the difference is not statistically significant. Based on best fit lines, the TCB/E-CIP strength ratio ranges from 1.02 to 0.95, with increasing embedment length, for No. 5 bars, and from 0.985 to 0.975 for No. 8 bars.

As shown in Fig. 3.3, the strengths of the epoxy-coated S-pattern cast-in-place and TCB grouted bars are nearly identical and slightly below the strength of the C-pattern TCB grouted bars. The observation that S-pattern bars provide slightly lower bond strengths than C-pattern bars matches earlier test results for cast-in-place epoxy-coated reinforcement (Choi et al. 1990, 1991).

No. 5 and No. 8 bars anchored with TCA exhibit significantly lower bond strengths than bars anchored with TCB (Figs. 3.1 and 3.2). Based on the best fit lines, the TCA/E-CIP strength ratio ranges from 0.76 to 0.78 for No. 5 bars and from 0.67 to 0.79 for No. 8 bars.

The relationships between bond force and embedment length are nearly linear for all of relationships illustrated in Figs. 3.1 and 3.2. The coefficients of determination, r^2, (see Appendix B) exceed 0.93 for No. 5 bars, and 0.90 for No. 8 bars, except for TCB bars, for which $r^2 = 0.87$ for both bar sizes. These coefficients of determination show that there is a strong linear relationship between bond strength and embedment length.

Bar diameter.–The effect of bar diameter on bond strength is illustrated in Fig. 3.4, which combines the results for the C-pattern uncoated and coated cast-in-place bars and TCA and TCB grouted bars from Figs. 3.1 and 3.2. Fig. 3.4 illustrates that, for 3 in. cover and the same embedment lengths, the No. 5 bars have lower bond strengths than the No. 8 bars. The effect of bar diameter is generally greater for the cast-in-place and TCB grouted bars than for the TCA grouted bars. For embedment lengths of 6 and 12 in., respectively, the No. 5/No. 8 strength ratios are 0.82 and 0.76 for uncoated (M) cast-in-place bars, 0.88 and 0.94 for epoxy-coated (E) cast-in-place bars, 0.90 and 0.87 for TCB grouted bars, and 0.97 and 0.90 for TCA grouted bars, based on the best fit lines. The observed effect of bar size on bond strength is not surprising since the effect of bar size on the development and splice strength of cast-in-place bars is well established (Orangun et al. 1975, 1977, Darwin et. al 1992a, 1992b).

Cover. –The effect of cover on bond strength is evaluated using C-pattern No. 5 bars, in Groups 19 and 22. Group 19 contained C-pattern uncoated and coated cast-in-place bars and coated TCA and TCB grouted bars with $1^1/_2$ in. cover. Group 22 contained C-pattern TCA and TCB grouted bars with 3 in. and $1^1/_2$ in. covers. The bond strength of bars with $1^1/_2$ in. cover are compared with the overall results for C-pattern bars with 3 in. cover (Groups 11, 15-17, 22) in Fig. 3.5. As expected, the reduction in concrete cover results in a reduction in bond force in all cases. For embedment lengths of 6 and 12 in. (as represented by the best fit lines in Fig. 3.5), the $1^1/_2$ in./3 in. cover strength ratios are, respectively, 0.86 and 0.99 for uncoated cast-in-place bars, 0.81 and 0.85 for coated cast-in-place bars, 0.86 and 0.91 for TCB-grouted bars, and 0.74 and 0.78 for TCA grouted bars. The relatively high sensitivity of the TCA-grouted bars to cover is somewhat unexpected, since the failure of these bars is governed by the grout-concrete interface. The failure of the cast-in-place and TCB-grouted bars is governed by splitting, which would suggest a greater, not lesser, dependency on cover. In none of these cases is bond strength as sensitive to cover as has been observed for the development and splice strength of cast-in-place bars (Darwin et al. 1992a, 1992b).

3.3 Horizontal Bars

Groups 18, 20, 21, and 24 are used to evaluate the bond strength of bars grouted in horizontal holes. No. 8 bars were used in Groups 18, 20, and 24, while No. 5 bars were used in Group 21. Both top-cast (3 in. top cover) and bottom-cast (3 in. bottom cover) bars were tested. No. 8 bars were cast-in-place or anchored in $1^1/_4$ in. holes with CPA, NSA, and TCA grouts; while No. 5 bars were cast-in-place or anchored in $^7/_8$ in. holes with CPA and TCA grouts. All bars were epoxy coated.

The No. 8 bar tests in Group 24 involved the placement of the compression bearing pad an additional $7^1/_2$ in. (12 vs. $4^1/_2$ in.) away from the center of the test bar. The movement of the compression bearing pad reduced the potential for increased bond strength due to the formation of a compressive strut between the bearing pad and the test bar. The purpose of modifying the test fixture was to determine the sensitivity of the test results to the placement of the bearing pad and determine the applicability of the test results to more general states of loading. The results obtained in Groups 18 and 20 are compared to those obtained in Group 24 in Figs. 3.6 and 3.7 for top and bottom-cast bars, respectively. Comparisons can be made for CPA, NSA, and TCA top bars, and for NSA and TCA bottom bars. The comparisons illustrate that the range of the test data is similar over the range of embedment lengths evaluated. The bars in Group 24 anchored with CPA and TCA increase in bond strength more rapidly with increasing embedment length than the bars in Groups 18 and 20, while the opposite is true for the NSA grouted bars. Since the test results are generally similar in nature, it appears that the differences in the best fit lines are due to the small samples involved, rather than any real difference in the bond behavior of the test bars. Based on these observations, the test results for Group 24 are combined with those from Groups 18 and 20. The results for No. 5 bars from Group 21 and the combined results for No. 8 bars are illustrated in Figs. 3.8 and 3.9 for top-cast and bottom-cast bars, respectively.

Fig. 3.8 shows that the cast-in-place and CPA grouted No. 8 bars have similar strengths. In fact, the CPA bars have higher strengths for embedment lengths of 9 in. or more. The No. 8 NSA and TCA grouted bars exhibit significantly lower strengths, with the NSA grouted bars exhibiting higher strengths than the TCA grouted bars. For ℓ_e = 6 and 15 in., the grouted/cast-in-place strength ratios are, respectively, 0.96 and 1.05 for CPA, 0.70 and 0.92 for NSA, and 0.65 and 0.84 for TCA.

For No. 5 bars, Fig. 3.8 shows that the cast-in-place bars are significantly stronger than the TCA grouted bars, which are stronger than the CPA grouted bars. The CPA grouted bars actually decrease in strength with increasing ℓ_e. As with vertically placed bars, horizontal No. 5 bars provide lower bond strengths than horizontal No. 8 bars with the same embedment length and anchoring method.

The behavior of the CPA grouted No. 5 bars (Fig. 3.8) represents a significant departure from the behavior observed for any other bars. The CPA No. 5 bars exhibit nearly equal strengths for $\ell_e = 4$ and 6 in., but progressively lower strengths for $\ell_e = 9$ and 12 in. The strength for $\ell_e =$ 6 in., is below that observed for the vertically placed No. 5 bars anchored with CPA grout. The low strength (at all embedment lengths) may be due to the fact that the hole diameter used for the CPA bars in Group 21, 7/8 in., is greater than the value of 13/16 in. recommended by the manufacturer and used earlier, in groups 1, 2, 4, 5, and 11. Since CPA grout contains aggregate particles, the size of which may play an important role in interlock as bond failure occurs, the greater gap between the reinforcing bar and the wall of the hole may have resulted in the lower capacity. This was not a factor for the No. 8 bars, since the hole diameter used for the No. 8 bars, 1 1/4 in., was that recommended by the manufacturer. The decreasing strength with increasing embedment may have also been due to the loading method, with the compression bearing plate within 4 1/2 in. of the test bar. The proximity of the bearing plate may have contributed to the strengths of the bars with 4 and 6 in. embedment, but not to the strength of the bars with 9 and 12 in. embedment, since in the case of capsules, only a portion of the bar is in contact with the grout. A comparison of these results with those obtained for the No. 8 CPA grouted bars suggests that the proper sizing of the hole with respect to the bar may be the dominant effect. The bond strength of the No. 8 bars increased continually with increasing embedment, even in Group 24 where the loading plate was 12 in. from the center of the test bar and in spite of the fact that the No. 8 bars were in contact with the grout for only about 8 in. In practice, more than one capsule would be used for the longer embedded lengths for both the No. 5 and No. 8 bars. For the No. 5 bars for $\ell_e = 4$ and 12 in., the grouted/cast-in-place strength ratios are, respectively, 0.94 and 0.69 for TCA and 0.92 and 0.05 for CPA based on the best-fit lines.

As shown in Fig. 3.9, the trends observed for top-cast bars are also exhibited by the bottom-cast bars, and the general relationships between anchorage methods carry over. Like the top-cast bars, the bottom-cast No. 5 bars exhibit lower strengths than the No. 8 bars for the same embedment lengths and anchorage methods. And, as for the top-cast bars, the No. 8 CPA grouted bars have slightly higher bond strengths than the cast-in-place bars, which are significantly stronger than the NSA and TCA grouted No. 8 bars. Cast-in-place No. 5 bars are stronger than TCA grouted No. 5 bars, and CPA grouted No. 5 bars decrease in bond strength with increasing development length; the CPA anchored No. 5 bars with ℓ_e = 4 in. and 6 in. have nearly identical strengths, while the bars with ℓ_e = 9 and 12 in. exhibit lower capacities.

Top-bar effect.–Using the best fit lines from Figs. 3.8 and 3.9, Figs. 3.10 and 3.11 compare the strengths of the top-cast and bottom-cast No. 8 and No. 5 horizontal bars, respectively. The figures show that the bottom-cast No. 8 bars exhibit higher strengths than the corresponding top-cast bars for all values of ℓ_e, and the bottom-cast No. 5 bars exhibit higher strengths for most values of ℓ_e. The TCA grouted No. 5 bars show the least effect of casting position. The higher capacity of the bottom-cast bars is likely due to the higher quality of the concrete at the bottom of the placement. Overall, the top-bar effect (ratio of bond strengths of bottom bars to top bars) based on the best-fit lines ranges from 1.08 to 1.10 for cast-in-place No. 8 bars, from 1.00 to 1.06 for cast-in-place No. 5 bars, from 1.06 to 1.15 for CPA grouted No. 8 bars, from 1.06 to 1.08 for NSA grouted No. 8 bars, from 1.03 to 1.06 for TCA grouted No. 8 bars, and from 0.96 to 1.02 for TCA grouted No. 5 bars [the top-bar effect for the CPA grouted No. 5 bars, which ranges from 0.85 to 3.13, is not of much practical interest, but is reported for completeness]. These values compare to top-bar factors of 1.3 and 1.4 used by the ACI Building Code (1989) and AASHTO Bridge Specifications (1989), respectively.

Comparison with vertically anchored bars.–Figs. 3.12 and 3.13 compare the bond strengths for horizontal top-cast and vertical No. 8 and No. 5 bars, respectively, and demonstrate that, in the cases illustrated, bond strength is largely independent of orientation. For the cast-in-place (CIP) and TCA anchored No. 8 bars (Fig. 3.12), the horizontal top-cast bars, on average, provide slightly higher strengths than the vertical bars (maximum difference in best fit lines = 1.66 kips for CIP and 1.68 kips for TCA). Comparisons for the CPA and NSA grouted bars can only be made based on the test data in Groups 8-10 (Table 2.5) since vertically anchored No. 8 bars with these grouts were tested only with 9 in. embedment lengths. In these cases, bond strength is somewhat more sensitive to bar orientation. For ℓ_e = 9 in., the CPA and NSA grouted horizontal top-cast bars have lower strengths than the corresponding vertical bars, 25.55 kips versus 28.23 kips for the CPA grouted bars and 20.55 kips versus 23.21 kips for the NSA grouted bars.

For the No. 5 cast-in-place and TCA grouted bars (Fig. 3.13), the horizontal top-cast bars have lower strengths than the vertical bars for most values of ℓ_e. These differences, however, may be more apparent than real since the data is very limited for the horizontal bars; the actual ranges of strength obtained for each development length overlap.

The strengths produced by the CPA grouted horizontal top-cast No. 5 bars are below those obtained by the CPA grouted vertical bars in Groups 1, 2, 4-6 and 11 (Table 2.5). For 6 in. embedment, modified strengths range from 9.96 to 15.26 kips for the vertical bars compared to 9.85 kips for the horizontal bar with 6 in. embedment. As discussed earlier, the lower strength of the horizontal bar may be due to the larger hole diameter used for the horizontal bars, $^7/_8$ in., compared to the manufacturer recommended hole diameter of $^{13}/_{16}$ in. used in Groups 1, 2, 4-6, and 11.

The overall similarity in bond strength between the top-cast horizontal and vertical bars is probably due to the similarity in concrete quality, since the vertical bars were all placed in the upper portion of the test specimens.

The relationship between the strength of horizontal bottom-cast bars and the strength of vertical bars is similar to that obtained between the horizontal bottom-cast bars and the horizontal top-cast bars.

3.4 Sloped Bars

Grouted reinforcing bars are often inserted at an angle, rather than perpendicular to the surface. To evaluate the effect of bar slope on bond strength, 15 No. 5 bars in Group 24 were inserted at a slope – six with a slope of 1:3 and nine with a slope of 1:6 (Fig. 2.1a). The bars were oriented such that the cover increased with increasing embedment. At the time of test, the specimens were positioned so that the bars were subjected to a direct tensile force (i.e., like the other test specimens). The test results are shown in Fig. 3.14.

When compared to the test results for both vertical bars and horizontal top-cast bars, the sloped bars generally exhibit strengths that are equal to or greater than the strengths of bars that are placed with uniform cover equal to the minimum cover on the sloped bar. In fact, the only two tests in which the steel failed in tension occurred in this test group (NSA and TCB grouted bars with ℓ_e = 12 in. and a 1:6 slope). The only bars to produce higher strengths than corresponding bars with constant cover were two NSA grouted bars with ℓ_e = 6 in. and a 1:6 slope. Considering the small amount of available data and the fact that the preponderance of that data indicates improved performance, it appears that it would be safe and economical to consider sloped reinforcement as equivalent to reinforcement placed with a constant cover equal to the minimum cover on the sloped bar.

3.5 Concrete Strength

Group 23 was used to provide insight into the effect of concrete strength on the bond capacity of anchored bars. The group consisted of 9 vertically anchored No. 5 bars, with 6 in. embedment. Three bars each were anchored with NSA, CPA, and TCA grouts. The concrete had a strength of 2700 psi at the time of the test.

The bond strengths exhibited by these bars are significantly below those provided by bars with nominal concrete strengths of 5000 psi (Table 2.5). However, when the bond strengths are multiplied by $(5000/f'_c)^{1/2}$, the modified bond strengths overlap the test results provided for vertically anchored No. 5 bars in Groups 1, 2, 4-6, and 11.

For NSA grout, the modified bond strengths in Group 23 range from 13.08 to 15.20 kips compared to a range of 10.92 to 17.42 for the earlier tests of vertical No. 5 bars with 6 in. embedment. For CPA grout, the modified bond strengths range from 6.98 to 13.51 in Group 23, compared to 9.96 to 18.52 in the earlier groups. And for TCA grout, the modified bond strengths range from 8.72 to 12.29 in Group 23, compared to 6.82 to 15.43 kips in earlier groups.

This limited comparison suggests that using the square root of the compressive strength is a reasonable way to account for the effect of concrete strength on the capacity of grouted reinforcing bars. The limited nature of the data also suggests that additional tests would be worthwhile.

3.6 Presence of Parallel Tensile Reinforcement

During the initial stages of the current study, there was some concern that the lack of tensile reinforcement in the concrete test specimen would result in tensile (T) failures of the concrete, rather than splitting (S), grout-concrete interface (IGC), or pullout failures, which are indicative of a failure in bond. That was the reason for the addition of auxiliary tensile reinforcement parallel to the test bar, starting with Group 4. However, the addition of the parallel auxiliary reinforcement does not seem to have had a significant effect on the test results, and a significant body of information developed for anchors in concrete indicates that tensile failures would not predominate (Collins et al. 1989, Cook et al. 1989). For that reason, additional tests were performed without tensile reinforcement in Groups 21 and 24. Five of the six No. 5 bars in Group 21 with no tensile reinforcement, NTR (Table 2.5), exhibited a combined IGC/T or S/T failure. However, the strengths produced in Group 21 are virtually identical to those produced in the earlier tests with tensile reinforcement (Groups 4-6, 15-17, 22) for bars anchored with TCB (Table 2.5).

The comparison of the No. 8 bar tests in Group 24 with the earlier tests (see Figs. 3.6 and 3.7 and Section 3.3) shows virtually no differences in the strength, although two very clear tensile failures did occur in Group 24 (for the CPA-grouted bar with ℓ_e = 12 in. and TCA-grouted bar with ℓ_e = 15 in.). In both of these cases, the tensile failure occurred at a strength that was above the overall trend line for the bars anchored with these grouting materials.

The test configurations used in this study, with covers of $1^1/_2$ and 3 in., allowed failure to occur without the strengths being dominated by tensile failure of the concrete. In general, when tensile failure did occur, the strengths were, as observed for Group 24, higher than the trend line of strengths obtained based on IGC, S or pullout failures. As a consequence of these observations, the design procedures that follow do not consider concrete tensile strength .

CHAPTER 4

RECOMMENDATIONS FOR DESIGN AND CONSTRUCTION

The recommendations that follow are based on the observations and evaluations presented in Chapters 2 and 3. The design procedures are selected to be moderately conservative and easy to apply. Current Kansas construction requirements (KDOT 1990) are simplified.

The design procedures recognize that: 1) different grouts exhibit different strengths, 2) individual grouts may provide different strengths when used to anchor bars in horizontal and vertical holes, 3) the bond strength provided by grouted bars drops with decreasing cover and decreasing center-to-center spacing (although the effect of spacing on bond was not evaluated in this study), and 4) the bond strength of a sloped bar can be conservatively represented by the strength of a bar with a constant concrete cover equal to the minimum cover on the sloped bar.

The approach that follows defines three strength classes of grout, Strength Class A, Strength Class B, and a Special Strength Class. The specific strength class is assigned based on tests that are similar to those used in this study. Strength Classes A and B are based on minimum strength requirements, while the Special Strength Class is provided to allow for the use of the actual test results.

4.1 Notation

A_b	=	Area of an individual bar, sq. in.
f'_c	=	Compressive strength of concrete, psi
$\sqrt{f'_c}$	=	Square root of concrete compressive strength, psi
f_s	=	Tensile stress in reinforcement, psi
f_y	=	Specified yield strength of reinforcement, psi
ℓ_e	=	Embedded length of grouted reinforcement, in.
T_e	=	Tensile force in grouted reinforcement, pounds
T_n	=	Nominal tensile force in grouted reinforcement, pounds
γ	=	Factor obtained in evaluating grout strength = $T_e(avg)/\ell_e\sqrt{f'_c}$

ϕ = Strength reduction factor

4.2 Definitions

Strength Class.–A category of grout based on the bond strength it provides for anchoring embedded reinforcement. The strength class of a grout should be established separately, and need not be the same, for horizontal and vertical bar installations. The procedures for establishing the strength class of a grout are presented in Appendix A.

Strength Class A grout.–A grout that provides a minimum average bond strength $T_e = A_b f_s = 30\, \ell_e \sqrt{f'_c}$ when tested in accordance with standard procedures (Appendix A).

Strength Class B grout.–A grout that provides a minimum average bond strength = 70 percent of that required of a Strength Class A grout.

Special strength class grout.–A grout that provides a minimum average bond strength $= T_e = A_b f_s = \gamma\, \ell_e \sqrt{f'_c}$ when tested in accordance with standard procedures (Appendix A).

Grout Strength Classes A and B were established using the test results for top-cast horizontal and vertical bars illustrated in Figs. 3.12 and 3.13 for No. 8 and No. 5 bars, respectively. The specific strength requirements defining the classes were selected primarily based on the strength properties of grouted No. 5 bars, since these provide lower bond strengths than larger bars with the same embedment length.

Two primary strength classes, A and B, were selected to both allow economical use of the highest strength grouts without preventing the use of lower strength grouts that may have desirable construction properties, such as rapid curing, but will require longer embedment lengths. The category of Special Strength Class is defined to allow virtually any grout to be used based on its actual performance. The strength of a Special Strength Class grout may be above or below that of Strength Classes A or B. The standard requirements for evaluating the strength of a grout require a minimum of three tests each at embedment lengths equal to 9 and 15 bar diameters. The bars are tested with a 3 in. cover. A general qualification as a Strength Class A, Strength Class B, or Special Strength Class grout requires the use of No. 5 bars. However, a Special Strength Class grout can be qualified using a bar size other than No. 5, but the application of that Special Strength Class will be limited to the bar size used in the test.

The requirements for Strength Class A and Strength Class B are compared with the test results for horizontal top-cast and vertical No. 5 and No. 8 bars in Figs. 4.1 and 4.2, respectively. As illustrated in Fig. 4.1, TCB grout in vertical holes would be qualified as a Strength Class A grout, while TCA in both vertical and top-cast horizontal holes would be qualified as a Strength Class B grout. CPA grout, as applied with a single capsule and oversize holes (not in accordance with the manufacturer's recommendations), would not meet the requirements of a standard strength class grout.

As illustrated in Fig. 4.2, the No. 8 bars provide higher strengths than the No. 5 bars. The figure shows that CPA grout and NSA grout in top-cast horizontal holes and TCB grout in vertical holes meet the requirements of a Strength Class A grout, while TCA grout in both horizontal top-cast and vertical holes provides strengths that place it in the upper range of Class B grouts. Under these proposed design procedures, the engineer has the option of using the lower strengths obtained with the No. 5 bars to establish the strength class or treating the No. 8 bars as belonging to a Special Strength Class to take advantage of their higher strength.

4.3 Design

Strength reduction factors.–Strength reduction factors, ϕ, are as follows:

(A) Steel yield strength . . . . $\phi = 0.90$

(B) Bond strength . . . . $\phi = 0.65$

A strength reduction factor of 0.90 is commonly used when strength is governed by tensile yielding of reinforcing steel (AASHTO 1989, ACI Committee 318 1989a, 1989b). A strength reduction factor of 0.65 is commonly used in cases where strength is governed by the tensile strength of concrete or the anchorage provided by a grout (ACI Committee 318 1989b, Cook et al. 1989).

Design tensile strength.–The design tensile strength of grouted reinforcement, ϕT_n, is calculated as the smaller of Eq. 4.1 and the applicable equation based on grout type, Eq. 4.2, Eq. 4.3, or Eq. 4.4.

$$\phi T_n = \phi A_b f_y \tag{4.1}$$

Strength Class A Grout:

$$\phi T_n = \phi \, 30 \ell_e \sqrt{f'_c} \tag{4.2}$$

Strength Class B Grout:

$$\phi T_n = \phi \, 21 \ell_e \sqrt{f'_c} \tag{4.3}$$

Special Strength Class Grout:

$$\phi T_n = \phi \, \gamma \ell_e \sqrt{f'_c} \tag{4.4}$$

Eqs. 4.2 and 4.3 produce predicted strengths equal to 78 and 55 percent, respectively, of the strength that would be calculated for cast-in-place bars using the expression for basic development length in the 1989 AASHTO Bridge Specifications and the 1989 ACI Building Code.

Modification factors based on cover and bar spacing.–The value of design strength, ϕT_n, calculated using Eqs. 4.2, 4.3, or 4.4 should be modified by a factor of 0.85 for bars anchored with a grout that meets the requirements of a Strength Class A grout and 0.75 for bars anchored with other grouts, if the bars have covers less than 3 in. or clear spacings less than 6 in. Covers less than $1\frac{1}{2}$ in. and clear spacings less than 3 in. should not be permitted. For bars with cover that changes along the embedded length, cover should be interpreted as minimum cover.

The different requirements for modification factors based on cover and bar spacing are based on observations made in Section 3.2 indicating that the bond strengths of bars anchored with Strength Class B grouts are more sensitive to low covers than the bond strengths of bars anchored with Strength Class A grouts. Both modification factors are less severe than the corresponding factors in ACI 318-89, reflecting the lower cover sensitivity of bars that are grouted compared to bars that are spliced or developed.

4.4 Construction Requirements

Current construction requirements for grouted reinforcing steel (Section 830, KDOT 1990) require: 1) that the holes be drilled $^1/_4$ in. ± $^1/_{16}$ in. larger than the diameter of the reinforcing steel; 2) that the hole be "thoroughly cleaned while dry and then scrubbed with a fiber brush and clear water to remove all traces of loose material"; and 3) that "after placing the . . . reinforcing steel the hole shall be completely filled with an approved epoxy grout or an approved nonshrink grout" that is "mixed, applied, and cured according to the manufacturer's recommendations or as directed by the Engineer." The construction requirements further specify that the concrete adjacent to the hole not be injured due to the drilling operation and that "the grout shall be applied so that the holes are completely filled and no voids exist between" the reinforcement and the concrete.

Based on the current study, the limitation on hole diameter and the use of water to clean the hole do not seem to be necessary requirements. Although the $^1/_4$ in. criteria for selecting the diameter of the hole is realistic in most cases, the use of a larger hole would not be detrimental for most of the grouts tested in this study. The only case in which hole diameter appears to be important is when capsules are used. Therefore, it is recommended that the construction requirements be modified to allow the use of "other hole diameters that have been demonstrated to provide adequate strength."

Specified cleaning methods should be modified to remove the requirement of using clear water to scrub the hole. Scrubbing with a fiber brush should be retained, followed by final hole satisfactory: "After the hole is drilled, it shall be thoroughly cleaned while dry and then scrubbed with a fiber brush, followed by filtered compressed air (oil and water free) to remove all traces of loose material."

The requirement that the reinforcing steel be placed before the hole is filled with grout should be changed to recognize that most installation procedures involve placement of the reinforcement after placement of the grout. This can be done by requiring that "the reinforcing steel shall be placed and the hole shall be completely filled in accordance with the manufacturer's directions . . ."

Finally, considering the variety of grouting materials that are available, it would be worthwhile to change the construction requirement to allow the use of "an approved grout", without referring to epoxy or nonshrink grouts.

CHAPTER 5

EVALUATION OF FIELD TEST METHOD

One of the goals of this project is to evaluate the applicability of a field test procedure, similar to a method used by the State of Kentucky (1991), for proof loading grouted reinforcing bars in the field. The procedure, Kentucky Method 64-209-91, involves proof testing of grouted reinforcing bars to 100 percent of their yield strength using a hollow core jack that is supported on metal plates that bear on the concrete adjacent to the reinforcing bar.

The test procedure is evaluated by comparing the strength and failure mode of grouted bars tested to failure with the field test apparatus to the strength and failure mode of bars anchored with the same grouts reported earlier in this study.

In addition to the field test, Kentucky Method 64-209-91 also includes a procedure for qualifying grouts. That test is also addressed briefly in this chapter.

5.1 Test Setup

The field test setup, as evaluated in this study (Fig. 5.1), consisted of a 60 ton hollow core jack supported on two curved "ram supports" that rested on two 8 x 8 x $1^1/_2$ in. plates that were placed adjacent to the test bar. The system was assembled based on photographs provided by Kentucky state transportation personnel.

As shown in Fig. 5.1, the plates were placed just to the outside of the hole in which the grouted reinforcing bar was anchored. A pulling head and bar wedge grips were used to apply the force at the top of the hydraulic jack. A hand pump was used to apply the hydraulic pressure. The pressure was calibrated versus force in a 120 kip Baldwin Universal Tester. Force was applied at approximately 2.5 kips per min.

5.2 Test Specimen

The standard beam-end test specimens (Fig. 2.1) were used to evaluate the field test procedure. Holes were drilled and grouted for the field tests using the same procedures used in balance of the study. Field tests were carried out after regular beam-end tests were completed for each specimen. No visible damage from the initial tests existed in the region of the field tests. Bars were anchored for the field tests in the same positions illustrated in Fig. 2.1a, with a 3 in. cover and centered 9 in. from the edge of the specimen.

5.3 Test Program

The test program consisted of 36 bars tested in four groups. Field Tests 1, 2, 3, and 4 were carried out in conjunction with Groups 18, 19, 20, and 23, respectively. CPA, NSA, TCA, and TCB grouts were evaluated. No. 5 bars were used for all tests.

Field Test 1 was carried out after all of the test cylinders had been broken for Group 18. An estimated compressive strength of 5600 psi was used based on the expected strength gain between 35 days (strength of 5400 psi for Group 18) and the test date of 45 days. In Field Tests 1, 3 and 4, the bars were drilled and anchored in the vertical position. Field Test 2 was carried out using bars that were anchored in horizontal bottom-cast positions. However, unlike the horizontal bars studied in the regular test series, these bars were grouted in a vertical position to allow comparison of TCB grout with the other grouts.

The three bars in Field Test 4 were used to evaluate the strength of bars in low strength concrete. Field Test 4 represents the only case in which the regular test bars and the field test bars were tested on the same day.

The bars in Field Tests 1 and 4 were anchored with embedment lengths of 9 and 6 in., respectively. Those in Field Tests 2 and 3 were anchored with embedment lengths of 6, 9, and 12 in.

5.4 Evaluation

The results obtained in the field tests are illustrated in Fig. 5.2, in which the combined results from Field Tests 1 and 3 are compared with the best-fit representations of vertically anchored TCA and TCB bars (Fig. 3.1) and for horizontal top-cast CPA grouted bars (Fig. 3.8). The results illustrated in Fig. 5.2 show that the field test bars are much less sensitive to embedment length than the bars tested using the regular configuration. For the TCA and TCB anchored bars, the field test provides significantly higher strengths at low embedment lengths than do the bars tested in the normal fashion. The differences narrow with increasing embedment, and the field test TCA bars actually exhibit slightly lower strengths at $\ell_e = 12$ in. than do the regular test bars. The CPA grouted bars provide similar strengths at a 6 in. embedment. With increasing embedment, the field test CPA bars exhibit higher strengths than do the regular CPA bars.

Field test NSA grouted bars, which are also illustrated in Fig. 5.2, cannot be compared directly to a best-fit line for NSA anchored No. 5 bars, since only 6 in. embedment was used in the regular test series for NSA grouted No. 5 bars. Comparison with the test results of vertically anchored NSA bars with $\ell_e = 6$ in. shows modified bond strengths of 24.57 kips in Field Test 2 and the 19.82 kips in Field Test 3 compared to a bond strength range of 12.81 to 18.4 kips in Groups 1, 2, 4-6.

A comparison of the test results for Group 23 illustrates significant differences in strength between the regular test procedure and the field tests (Field Test 4) for two out of the three grouts. For $\ell_e = 6$ in. (used for all bars in Group 23), the regular CPA grouted bars have an average modified bond strength of 10.34 kips, compared to a field test strength of 19.5 kips. The TCA grouted bars have an average modified bond strength of 10.32 kips, compared to a strength of 23.88 kips for the field test. Only the NSA grouted bars exhibited similar strengths, 14.37 for the regular bars and 13.36 for the field test bars.

Overall, field test bars exhibit significantly higher bond strengths at development lengths of 6 and 9 in. than do bars loaded under more realistic conditions. The relationship between embedment length and bond strength exhibited in the field tests is not indicative of the actual behavior of the bars. The key difference between the field tests and the regular beam-end tests is the high confining stresses provided by the load plates in the field tests. These confining stresses are not present in actual structures.

Failure Mode.–For the CPA and TCA grouted bars, failure modes in the field tests match those observed in the earlier tests. The CPA bars in the field tests (anchored in $^7/_8$ in. diameter holes) exhibited a pullout failure, the same failure mode exhibited by CPA grouted bars in

$^{7}/_{8}$ in. diameter holes tested earlier. As with the earlier tests, the TCA grouted bars uniformly exhibited a failure at the grout-concrete interface (IGC). That these failure modes do not change is not surprising since the nature of the field test setup mitigates against failure of the surrounding concrete.

The effect of the test setup on failure mode is significant for the NSA and TCB grouted bars. In the field tests, of ten NSA grouted bars, two failed by splitting (S) and eight bars failed by pullout. Of nine TCB grouted bars, two failed by splitting, four failed by pullout, and three failed at the grout-concrete interface (IGC). These observations differ significantly from the earlier test results (Table 2.5) in which the failure of bars anchored with both grouts was dominated by splitting of the concrete. The confining compressive stresses provided by the base plates in the field tests served to strengthen the concrete and force the failure to occur at the grout-concrete or grout-reinforcement interface.

As mentioned at the beginning of the chapter, Kentucky Method 64-209-91 includes a procedure for qualifying grouts. Like the field test, the qualifying test involves the application of compressive stresses to the concrete surface adjacent to the test bar. Therefore, the qualifying procedures should also be expected to give results that do not accurately represent bond behavior.

5.5 Summary

The field tests, as executed in this study (Fig. 5.1), do not provide a good measure of the behavior, strength or safety of grouted reinforcement. The strength of bars with lower values of embedment length appear to be significantly higher than those provided by bars loaded under more realistic conditions and the bond strengths of bars tested with the field test apparatus are much less sensitive than "beam-end" test bars to increases in embedment length. These differences in strength are due primarily to differences in the loading conditions, which tend to force failure in the region of the bar and limit participation of the concrete.

Modified Test.–These results suggest that a modified version of the field test could be developed that would give a realistic measure of bond strength. In the modified version of the test, rather than supporting the jack on base plates that are adjacent to the test bar, the jack should be supported by a flexural member that is supported by the concrete on each side of test bar at a distance equal to at least the embedment length, ℓ_e, as shown in Fig. 5.3. The modified test procedure would eliminate the compressive stresses in the region of the bar caused by the base plates.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

This report describes the effects of hole preparation method, grout type, hole diameter, bar size, embedment length, cover, reinforcing bar deformation pattern, bar surface condition (epoxy coated or uncoated), orientation of the installed bar, and concrete strength on the bond strength of grouted reinforcing bars to concrete. The study involves the evaluation of four hole preparation methods, including drilling with a high speed vacuum drill and drilling with a hand-held pneumatic hammer drill and cleaning with a fiber bottle brush and water, a fiber bottle brush without water, or with compressed air only. Two capsule systems, two two-component grout systems, and two nonshrink grout systems are evaluated. Hole diameters range from $^{3}/_{4}$ to $1^{1}/_{2}$ in. for No. 5 bars; $1^{1}/_{4}$ in. holes are used for No. 8 bars. Embedment lengths range from 4 to 12 in. for No. 5 bars and from 6 to 15 in. for No. 8 bars. $1^{1}/_{2}$ in. and 3 in. covers are used. Two bar deformation patterns are tested, and both epoxy-coated and uncoated bars are evaluated. Bar installations include vertical bars and near vertical sloped bars installed in the top portion of test specimens, and horizontal bars installed in the top and bottom portions of test specimens. Concrete strengths range from 2700 to 5900 psi. The tests are used to develop rational design and construction requirements. A standard test to establish the Strength Class of a grout for anchoring reinforcing bars is proposed. In addition, a test method currently in use by one state department of transportation is evaluated as a technique for proof-testing grouted reinforcement in the field.

6.2 Conclusions

The following conclusions are based on the tests and evaluations presented in this report.

1. For the techniques evaluated in this study, the bond strength of grouted reinforcing bars is not highly sensitive to differences in hole preparation method. Drilling methods that do not damage the surrounding concrete and most hole cleaning methods are satisfactory for most grouts. Grouts that tend to exhibit a bond failure

at the interface between the grout and the concrete (IGC) may provide higher strengths with more thorough cleaning methods. The vacuum drilling procedure appears to provide the best strength for grouts that exhibit IGC failures. However, this method is not required nor does it give the highest strength for most other grout installations. Cleaning with a fiber bottle brush and compressed air is recommended.

2. There can be significant differences in grout strength. Grouts that provide a strong bond at the grout-concrete interface provide higher bond strengths than grouts that undergo failure at the grout-concrete interface.
3. The bond strength provided by most grouts is not sensitive to the hole diameter. However, bond strength may be severely decreased for bars anchored with capsules, if the hole diameter is too large.
4. Bond strength increases with increasing embedment length.
5. For a given embedment length, bond strength increases with increasing bar size.
6. Bond strength increases with increasing cover. The bond strength of both cast-in-place and grouted reinforcing bars subjected to tension at the surface of concrete appears to less sensitive to cover than is the strength of cast-in-place spliced and developed reinforcement within reinforced concrete members.
7. The bond strength of grouted reinforcement is somewhat sensitive to the reinforcing bar deformation pattern. The degree of sensitivity appears to be similar to that observed for cast-in-place epoxy-coated reinforcement.
8. Cast-in-place epoxy-coated reinforcement provides a lower bond strength than cast-in-place uncoated reinforcement. Grouted epoxy-coated reinforcement and grouted uncoated reinforcement provide similar bond strengths.
9. Grouted vertically anchored bars and grouted top-cast horizontally anchored bars provide similar strengths for some grouts and different strengths for other grouts. Therefore, it is recommended that grouts be qualified separately for anchorage at

each orientation. Grouted horizontal top-cast reinforcement provides a lower bond strength than grouted horizontal bottom-cast reinforcement.

10. The bond strength of a sloped bar can be conservatively represented by the bond strength of a bar with a constant concrete cover equal to the minimum cover on the sloped bar.
11. For the grouts tested, bond strength increases approximately with the square root of the concrete compressive strength.
12. The proposed standard test method for evaluating the bond strength of grout for anchoring reinforcing bars is incorporated in a conservative yet easy-to-use design procedure.
13. The test method in use by the State of Kentucky to proof-test grouted reinforcement in the field is not recommended because the failure modes are often different and the strengths are higher than those obtained under more realistic loading conditions. A modification is suggested in which the points of bearing on the concrete are placed away from the test bar.

6.3 Future Work

Based on the results of the current study, a number of outstanding questions remain on the subject of the bond strength between grouted reinforcing bars and concrete.

In the current study, a relatively small number of tests were carried out with covers less than 3 in. All test specimens involved significant side covers and no specimens involved the test of more than one reinforcing bar at a time. Considerably more information is, therefore, desirable on the bond strength of reinforcing bars with covers other than 3 in. and on the bond strength of groups of reinforcing bars with different values of cover and bar spacing. The capacity of clustered groups of grouted reinforcing bars, for which failure may be dominated by group interaction rather than the strength of the individual bars, should be studied.

All of the tests in the current study were short-term tests, lasting but a few minutes. Presumably, different grouts exhibit different time-dependent behavior, and a grout that provides satisfactory strength in the short term may not provide satisfactory strength over a longer period of time. Therefore, it would be prudent to investigate the long-term performance of grouts, especially those that will carry significant sustained loading. It may also be desirable to include requirements for long-term strength when specifying grouts.

The proposed standard test for evaluating grouts, which appears in Appendix A, is based on the test specimen used in this study. It would seem to be prudent to evaluate other test configurations to determine if equivalent or superior test procedures could be developed.

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Table 2.1: Test Bar Data

Bar Size No.	Def Pattern	Yield Strength (ksi)	Def. Height (in.)	Def. Spacing (in.)	Def. Gap (in.)	Def. Angle (deg.)
5*	C	72.3	0.041	0.413	0.116	60
5**	C	72.3	0.040	0.413	0.140	60
5***	C	65.5	0.041	0.403	0.182	60
5	S	70.6	0.031	0.423	0.159	90
8***	C	69.0	0.062	0.654	0.165	60
8+	C	67.6	0.064	0.590	0.285	60
8++	C	+++	0.062	0.656	0.195	60

* Used for epoxy-coated (E) bars; except as noted

** Used for uncoated (mill scale surface = M) bars, except as noted

*** Used for uncoated (M) bars in Groups 15-17, 19

\+ Used for uncoated (M) bars in Groups 12-14

++ Used for horizontal bars in Group 24

+++ Yield strength is greater than 70.0 ksi

Table 2.2: Concrete Mixture Proportions (Cubic Yard Batch Weights)

Group	Nominal Strength (psi)	W/C ratio	Cement (lb)	Water (lb)	Aggregate Fine+ (lb)	Aggregate Coarse++ (lb)
1	5000	0.46	520	240	1525	1525
2	5000	0.42	544	230	1595	1595
4-22,24	5000	0.43	520	225	1545	1545
23	2500	0.46	496	228	1508	1565

\+ Kansas River Sand - Lawrence Sand Co., Lawrence, KS, bulk specific gravity (ssd) = 2.62, absorption = 0.5%, fineness modulus = 3.0.

++ Crushed limestone - Fogel's Quarry, Ottawa, KS, bulk specific gravity (ssd) = 2.57 absorption = 3.0%, nominal maximum size = $^3/_4$ in., unit weight = 90.5 lb/cu. ft.

Table 2.3: Concrete Properties

Group	Slump (in.)	Concrete Temperature (F)	Age at Test (days)	Grout Age at Test (days)	Air Content %	Average Compressive Strength (psi)
1	$3^1/_2$	78	69	3-4	*	5340
2	4	78	41	5-6	3.1	5350
			42			5500
4	2	72	78	3-4	1.9	5460
5	$2^1/_2$	74	56	4-5,7	5.6	5570
6	3	63	33	7	5.8	5250
			34	8		5530
7	$3^1/_2$	51	16	3	5.8	4460
8	3	52	24	3	5.9	4710
9	$3^1/_4$	45	27	3	6.4	5360
10	$3^1/_2$	52	20	3	5.5	4970
11	$3^1/_2$	52	31	4	6.4	5230
12	$2^3/_4$	64	25	3	6.2	5270
13	3	59	21	3	5.2	5600
14	$4^5/_8$	60	22	3	6.6	4550
15	$1^3/_4$	62	25	3	5.0	5360
			26	4		5480
			46	24		5870
16	$4^3/_4$	68	39	3-4	6.2	4610
17	$3^1/_4$	70	27	3	5.3	4980
18	$3^1/_4$	67	35	3	5.6	5400
			45	3		5600
19	$6^1/_2$	68	26	5	6.4	3960
			31	3		4270
20	$2^1/_2$	69	47	3	4.9	5230
			57	3		5490
21	3	66	26	3	5.8	4410
			27			4660
			44	3		5270
22	$2^3/_4$	67	24	3	4.8	4980
23	$4^3/_4$	62	5	3	6.8	2700
24	$3^1/_2$	59	22	3	5.8	4600
			29	7		4740
			53	31		4980
			53	6-7		4980**

* Not measured

** Horizontal Bars

Table 2.4: Grout Data

Grout Symbol:	CPA*
Manufacturer:	Hilti, Inc. 5400 S. 122nd East Avenue Tulsa, OK 74146
Grout Trade Name and Description:	HEA Adhesive Capsule Vinyl ester resin system packed in sealed glass tubes. Part A is in the outer tube and Part B is in the inner tube.
Ingredients:	Part A: Styrene, vinyl ester resin Part B: Dibenzoyl peroxide, silica sand

Appropriate diameter capsule ($^5/_8$ x 5 in. or 1 in. x 8$^1/_4$ in.) was inserted into a predrilled hole. Recommended hole diameter = $^{13}/_{16}$ in. for No. 5 bars and 1 $^1/_4$ in. for No. 8 bars. The rebar was inserted in setting tool mounted on a TE-72 Hilti rotary hammer drill. The end of the rebar with a 45° cut on it was placed on top of the capsule. The drill was switched on, and the rebar was drilled to the bottom of the hole with rotary hammer drill set in the hammer/rotation mode. The curing time varied based on the temperature of the base concrete.

Grout Symbol:	CPB
Manufacturer:	RAWLPLUG CO., Inc. P.O.Box 641 New Rochelle. NY 10802-9978
Grout Trade Name and Description:	Chem-Stud Capsule The Chem-Stud adhesive is packaged in single use (outer & inner) glass capsules which have premeasured components.
Ingredients:	Outer Capsule: Polyester resin, quartz aggregate Inner Capsule: Benzol peroxide hardening agent

A $^5/_8$ in. capsule was inserted into a predrilled hole. The rebar was inserted in setting tool mounted on a TE-72 Hilti rotary hammer drill. The end of the rebar with a 45° cut on it was placed on top of the capsule. The drill was switched on, and the rebar was drilled to the bottom of the hole with rotary hammer drill set in the hammer/rotation mode. The curing time varied based on the temperature of the base concrete.

Grout Symbol:	TCA*
Manufacturer:	Hilti, Inc. 5400 S. 122nd East Avenue Tulsa, OK 74146
Grout Trade Name and Description:	HIT C-100 Adhesive Material is packed in two tubes joined together. Part A is located in the larger tube, part B is located in the smaller tube.
Ingredients:	Part A: Vinyl ester resin, unsaturated polyester resin styrene, fumed silica, silica sand Part B: Dibenzoyl peroxide, fumed silica, paraffin wax, micro hollow balls

HIT C-100 adhesive was injected into the hole using a Hilti P-2000 manual dispenser. Rebar was rotated by hand during installation to insure proper adhesion between grout and rebar. The gel time and cure time of the grout varied based on the temperature of the base concrete.

Grout Symbol:	TCB
Manufacturer:	The Carter-Waters Corporation 2440 West Pennway P. O. Box 412676 Kansas City, MO 64141
Grout Trade Name and Description:	CWC 202, Type I A two component 100% solids, moisture insensitive, multipurpose structural epoxy bonding agent.
Ingredients:	Component A (epoxy resin) - Bisphenol A diglycidyl ether resin Component B - Polysulfied polymer, dimethylaminomethylphenol, 2,4,6, - Tri (Dimethylaminomethyl) phenol

Bonding Agent designed for application temperatures between 68°F and 104°F. Two component bonding agent was mixed in a 2:1 ratio by volume (two parts part A-resin, one part B-curing agent) for three minutes using a paint mixer blade mounted on a $^1/_4$ in. drill. Blending took place at low speed to avoid the formation of air bubbles in the mix. The grout, having a honey consistency, was poured directly into the hole, and rebar was rotated by hand during installation to insure proper adhesion. The grout had a pot life of 30 min. and a cure time of 24 hours at 75° F.

Grout Symbol:	NSA*
Manufacturer:	Cormix Construction Chemicals P. O. Box 190970 Dallas, TX 75219-0970
Grout Trade Name and Description:	Non-shrink Supreme Grout. A non-metallic grout, packaged in 55 lb. poly-lined bags.
Ingredients:	Silica aggregates, cements, a shrinkage compensating system, and plasticizing agents.

The non-shrink grout had a water requirement of 1 $^1/_4$ - 1$^1/_2$ gal. per 55 lb. bag for a fluid state and a yield of $^1/_2$ ft^3 per bag. For fluid consistency, $^3/_4$ of the required water was placed in the container, grout was added slowly while mixing using the drill mounted mixer blade to the point of stalling the mixer. Grout was mixed to a doughy state until all dry material was thoroughly wet. After all lumps had disappeared, the remaining water was added. Mixing continued for a total of 3-5 min. or until a uniform consistency was achieved.

Since small batches were mixed at each placement, grout and water required were carefully measured based on 1 $^1/_2$ gal. per bag requirement. To avoid air pockets and insure complete filling of the hole, the grout was placed from one side of the hole only. Rebar was rotated by hand during installation to insure proper adhesion between grout and rebar. Care was exercised not to overwork the grout in order to avoid segregation or bleeding. Exposed grout surfaces around the rebar were sealed with duct tape for a minimum of 3 days. Working time was approximately 20 min. Setting time was approximately 25-30 min.

Grout Symbol:	NSB
Manufacturer:	Master Builders, Inc. 23700 Chagrin Boulevard Cleveland, Ohio 44122-5554
Grout Trade Name and Description:	MASTERFLOW 814 Cable Grout A one component cement-based grout packaged in 55 lb moisture-resistant bags.
Ingredients:	Portland Cement and other cementituous materials and materials that protect against stress corrosion and hold to a minimum all components including chlorides and sulfides.

Grout had a 2.55 gal. water requirement per 55 lb. bag, producing approximately 0.65 ft^3 of fluid grout. Required water and grout were carefully measured. Water was placed in a container. With the drill mounted mixer blade operating, grout was added steadily and mixed for 2-3 minutes until the grout was uniform and essentially free of lumps. To avoid air pockets and insure complete filling of the hole, the grout was placed from one side of the hole only. Rebar was rotated by hand during installation to insure proper adhesion between grout and rebar. Care was exercised not to overwork the grout in order to avoid segregation or bleeding. Exposed surfaces were moist cured for 24 hours and sealed thereafter for a minimum of 3 days.

*Horizontal Rebar Placement, CPA, NSA and TCA only:

For CPA and TCA, same procedure as described above.

For NSA, all of the required water was placed in the mixer (rather than 3/4 as described above) and the grout was mixed to a doughy state. This produced a slightly stiffer grout. The only other difference compared to vertical bars was the method of grout placement in the horizontal hole. A dessert decorator with plastic tubing fitted at the end was custom made so that the grout could flow smoothly into the hole by means of injection. Care was exercised to fill up the hole as fully as possible prior to rebar placement.

Rebars were supported using a special bracing fitted around the concrete block.

Table 2.5: Test Results

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
			Groups 1 and 2				
1	5VC-M-6-7/8BW	NSA-NTR	3	5310	17.95	17.42	Pullout
2	5VC-M-6-7/8BW	NSA-NTR	2-15/16	5360	16.61	16.05	T
Avg						16.74	
1	5VC-M-6-13/16BV	CPA-NTR	3	5310	18.75	18.20	S
2	5VC-M-6-13/16BV	CPA-NTR	3-1/8	5360	19.17	18.52	S/T
Avg						18.36	
1	5VC-M-6-3/4BW	TCA-NTR	2-15/16	5310	14.38	13.96	IGC
2	5VC-M-6-3/4BW	TCA-NTR	3-1/16	5360		15.43	IGC/Cone
Avg						14.69	
1	5VC-M-6-7/8BA	NSA-NTR	3	5310	16.03	15.56	S
2	5VC-M-6-7/8BA	NSA-NTR	3-1/8	5510	15.25	14.53	Cone
Avg						15.05	
1	5VC-M-6-13/16BA	CPA-NTR	2-15/16	5390	14.85	14.30	Pullout
2	5VC-M-6-13/16BA	CPA-NTR	2-7/8	5360	18.48	17.86	S
Avg						16.08	
1	5VC-M-6-3/4BA	TCA-NTR	2-3/4	5310	8.16	7.92	IGC
2	5VC-M-6-3/4BA	TCA-NTR	3	5360	12.75	12.32	IGC/Cone
Avg						10.12	
1	5VC-M-6-7/8A	NSA-NTR	3	5390	13.30	12.81	IGC
2	5VC-M-6-7/8A	NSA-NTR	3-1/16	5510	17.91	17.07	S
Avg						14.94	
1	5VC-M-6-13/16A	CPA-NTR	3-1/8	5310	18.56	18.02	Pullout
2	5VC-M-6-13/16A	CPA-NTR	2-15/16	5360	17.00	16.43	Pullout
Avg						17.22	
1	5VC-M-6-3/4A	TCA-NTR	2-15/16	5390	9.69	9.33	IGC/Cone
2	5VC-M-6-3/4A	TCA-NTR	2-7/8	5360	10.93	10.56	IGC/Cone
Avg						9.95	
1	5VC-M-6-1.5BW	NSA-NTR	2-3/4	5310	15.65	15.19	S
2	5VC-M-6-1.5BW	NSA-NTR	2-5/8	5360	14.22	13.74	S/T
Avg						14.47	
1	5VC-M-6-1.5BW	TCA-NTR	3	5390	9.52	9.17	IGC
2	5VC-M-6-1.5BW	TCA-NTR	2-5/8	5360	9.22	8.91	IGC/S/Cone
Avg						9.04	
1	5VC-M-6-1.5BA	NSA-NTR	2-3/4	5390	16.05	15.46	IGC/S
2	5VC-M-6-1.5BA	NSA-NTR	3	5360	19.10	18.46	T
Avg						16.96	
1	5VC-M-6-1.5BA	TCA-NTR	3	5310	11.25	10.92	IGC
2	5VC-M-6-1.5BA	TCA-NTR	2-15/16	5510	12.51	11.92	IGC

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
Avg						11.42	
1	5VC-M-6-1.5A	NSA-NTR	2-13/16	5310	15.80	15.34	T
2	5VC-M-6-1.5A	NSA-NTR	2-11/16	5360	15.24	14.73	S/T
Avg						15.03	
1	5VC-M-6-1.5A	TCA-NTR	2-7/8	5360	13.71	13.25	IGC
2	5VC-M-6-1.5A	TCA-NTR	2-11/16	5510	9.87	9.40	IGC
Avg						11.33	
1	5VC-M-6	CIP-NTR	3	5310	15.31	14.86	T
2	5VC-M-6	CIP-NTR	3-1/16	5510	14.56	13.87	S/T
Avg						14.37	
1	5VC-E-6	CIP-NTR	3	5310	15.40	14.95	T
2	5VC-E-6	CIP-NTR	3-1/16	5510	14.63	13.94	S/T
Avg						14.44	
			Groups 4, 5 and 6				
4	5VC-M-6-7/8BW	NSA	3	5460	17.15	16.41	S
5	5VC-M-6-7/8BW	NSA	2-15/16	5570	15.74	14.91	T
6	5VC-M-6-7/8BW	NSA	2-15/16	5410	14.46	13.90	S
Avg						15.08	
5	5VC-E-6-7/8BW	NSA	3	5570	16.14	15.29	S
6	5VC-E-6-7/8BW	NSA	2-3/4	5410	11.36	10.92	S
Avg						13.11	
4	5VC-E-6-7/8BW	NSB	2-7/8	5460	14.88	14.24	S/Cone
5	5VC-E-6-7/8BW	NSB	3-1/16	5570	15.26	14.46	S/Cone
6	5VC-E-6-7/8BW	NSB	3	5410	14.38	13.82	S
Avg						14.17	
4	5VC-E-6-7/8BW	TCB	3-1/16	5460	18.77	17.96	S
5	5VC-E-6-7/8BW	TCB	2 13/16	5570	16.91	16.02	S
6	5VC-E-6-7/8BW	TCB	2-7/8	5410	14.00	13.46	S
Avg						15.81	
4	5VC-E-6-3/4BW	CPB	3	5460	11.59	11.09	S/Cone
5	5VC-E-6-3/4BW	CPB	2-7/8	5520	11.25	10.66	S/Cone
6	5VC-E-6-3/4BW	CPB	3	5410	7.64	7.34	IGC/Cone
Avg						9.70	
4	5VC-E-6-13/16BW	CPA	3	5460	13.44	12.86	S
5	5VC-E-6-13/16BW	CPA	2-13/16	5570	10.51	9.96	S
6	5VC-E-6-13/16BW	CPA	3-1/16	5410	10.70	10.29	S
Avg						11.04	
4	5VC-M-6-7/8BW	TCA	3-1/16	5460	11.20	10.72	IGC/S
5	5VC-M-6-7/8BW	TCA	2-15/16	5570	13.35	12.65	S/T

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
6	5VC-M-6-7/8BW	TCA	2-15/16	5410	7.61	7.32	T
Avg						10.23	
4	5VC-E-6-7/8BW	TCA	2-15/16	5460	13.49	12.91	IGC/S/Cone
5	5VC-E-6-7/8BW	TCA	2-7/8	5570	12.79	12.12	IGC/S/Cone
6	5VC-E-6-7/8BW	TCA	2-7/8	5410	10.59	10.18	IGC/T/Cone
Avg						11.74	
4	5VC-M-6-1.5BW	NSA	2-11/16	5460	16.20	15.50	S
5	5VC-M-6-1.5BW	NSA	2-5/8	5570	15.03	14.24	S/T/Cone
6	5VC-M-6-1.5BW	NSA	2-7/8	5410	13.38	12.86	S
Avg						14.20	
4	5VC-E-6-1.5BW	NSA	3-1/16	5460	16.74	16.02	S
5	5VC-E-6-1.5BW	NSA	2-3/4	5570	15.90	15.06	S
6	5VC-E-6-1.5BW	NSA	3-1/16	5410	14.28	13.73	S/Cone
Avg						14.94	
4	5VC-E-6-1.5BW	NSB	2-13/16	5460	14.98	14.34	Cone
5	5VC-E-6-1.5BW	NSB	2-13/16	5570	14.94	14.15	S
6	5VC-E-6-1.5BW	NSB	3-1/16	5410	14.21	13.66	S
Avg						14.05	
4	5VC-E-6-1.5BW	TCB	2-3/4	5460	16.26	15.56	S
5	5VC-E-6-1.5BW	TCB	2-7/8	5570	16.05	15.21	S
6	5VC-E-6-1.5BW	TCB	2-7/8	5410	14.76	14.19	T
Avg						14.99	
4	5VC-M-6-1.5BW	TCA	2-7/8	5460	12.30	11.77	IGC/Cone
5	5VC-M-6-1.5BW	TCA	3	5570	14.67	13.90	IGC/S
6	5VC-M-6-1.5BW	TCA	2-15/16	5410	12.08	11.61	IGC/S/Cone
Avg						12.43	
4	5VC-E-6-1.5BW	TCA	2-5/8	5460	12.65	12.11	IGC/Cone
5	5VC-E-6-1.5BW	TCA	2-11/16	5570	14.52	13.76	IGC/S/Cone
6	5VC-E-6-1.5BW	TCA	2-13/16	5410	12.27	11.80	IGC/S/Cone
Avg						12.52	
4	5VC-M-6-1.5BA	NSA	3	5460	17.79	17.02	S
5	5VC-M-6-1.5BA	NSA	2-13/16	5570	15.49	14.68	S
6	5VC-M-6-1.5BA	NSA	2-7/8	5410	14.90	14.32	S
Avg						15.34	
4	5VC-M-6-1.5A	NSA	2-7/8	5460	16.84	16.12	T
5	5VC-M-6-1.5A	NSA	3	5570	16.52	15.65	IGC/S
6	5VC-M-6-1.5A	NSA	2-7/8	5410	15.32	14.73	S
Avg						15.50	
4	5VC-M-6	CIP	3-1/16	5460	16.82	16.10	S
5	5VC-M-6	CIP	3	5570	17.50	16.58	S/Cone

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
6	5VC-M-6	CIP	3	5410	16.34	15.71	S
Avg						16.13	
4	5VC-E-6	CIP	3	5460	17.73	16.97	S
5	5VC-E-6	CIP	3	5570	17.16	16.26	S/Cone
6	5VC-E-6	CIP	3	5410	15.57	14.97	S
Avg						16.06	
			Group 7				
7	5VC-E-6-7/8BW	TCB	3-3/16	4460	9.92	10.50	IGC/Cone
7	5VC-E-6-7/8BW	TCB	3-3/16	4460	8.29	8.78	IGC/Cone
7	5VC-E-6-7/8BW	TCB	3-5/16	4460	11.06	11.17	IGC/Cone
Avg						10.33	
7	5VC-E-6-7/8BA	TCB	3-1/16	4460	8.36	8.85	Cone
7	5VC-E-6-7/8BA	TCB	3-1/8	4460	13.18	13.96	S/Cone
7	5VC-E-6-7/8BA	TCB	3-1/4	4460	11.61	12.29	S/Cone
Avg						11.70	
7	5VC-E-6-7/8A	TCB	3-1/4	4460	13.70	14.51	S/Cone
7	5VC-E-6-7/8A	TCB	3-1/8	4460	13.74	14.55	S
7	5VC-E-6-7/8A	TCB	3-1/4	4460	14.65	15.51	S/Cone
Avg						14.86	
			Groups 8, 9 and 10				
8	8VC-E-9-1.25V	NSA	3	4710	24.62	25.37	S
9	8VC-E-9-1.25V	NSA	2-7/8	5360	24.96	24.11	S
10	8VC-E-9-1.25V	NSA	3	4970	24.89	24.97	S
Avg						24.81	
8	8VC-E-9-1.25BW	NSA	3	4710	24.89	25.64	S
9	8VC-E-9-1.25BW	NSA	3	5360	22.86	22.08	S
10	8VC-E-9-1.25BW	NSA	3-1/4	4970	27.79	27.87	S
Avg						25.20	
8	8VC-E-9-1.25BA	NSA	3	4710	23.35	24.06	S
9	8VC-E-9-1.25BA	NSA	3-3/16	5360	21.16	20.44	S
10	8VC-E-9-1.25BA	NSA	3-1/16	4970	25.07	25.15	S
Avg						23.21	
8	8VC-E-9-1.25A	NSA	3	4710	21.66	22.32	S
9	8VC-E-9-1.25A	NSA	2-7/8	5360	24.14	23.32	S
10	8VC-E-9-1.25A	NSA	3	4970	26.13	26.21	S
Avg						23.95	

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
8	8VC-E-9-1.25V	TCB	3-3/16	4710	24.24	24.98	S
9	8VC-E-9-1.25V	TCB	2-7/8	5360	28.41	27.44	S
10	8VC-E-9-1.25V	TCB	3	4970	22.22	22.29	S
Avg						24.90	
8	8VC-E-9-1.25BW	TCB	3	4710	21.53	22.18	S
9	8VC-E-9-1.25BW	TCB	3-1/16	5360	28.40	27.43	S
10	8VC-E-9-1.25BW	TCB	3-1/16	4970	24.52	24.59	S
Avg						24.74	
8	8VC-E-9-1.25BA	TCB	3-1/16	4710	25.80	24.06	S
9	8VC-E-9-1.25BA	TCB	3	5360	25.76	20.44	S
10	8VC-E-9-1.25BA	TCB	2-7/8	4970	23.20	25.15	S
Avg						24.91	
8	8VC-E-9-1.25A	TCB	3-1/16	4710	23.62	24.34	S
9	8VC-E-9-1.25A	TCB	3-1/8	5360	26.20	25.30	S
10	8VC-E-9-1.25A	TCB	3	4970	24.81	24.88	S
Avg						24.84	
8	8VC-E-9-1.25V	CPA	3	4710	26.12	26.91	S
9	8VC-E-9-1.25V	CPA	2-15/16	5360	26.06	25.17	S
10	8VC-E-9-1.25V	CPA	3-1/8	4970	24.97	25.05	S
Avg						25.71	
8	8VC-E-9-1.25BW	CPA	3	4710	27.30	28.13	S
9	8VC-E-9-1.25BW	CPA	2-7/8	5360	25.15	24.29	S
10	8VC-E-9-1.25BW	CPA	2-15/16	4970	27.60	27.68	S
Avg						26.70	
8	8VC-E-9-1.25BA	CPA	3-1/8	4710	27.81	28.65	S
9	8VC-E-9-1.25BA	CPA	3-1/16	5360	27.63	26.69	S
10	8VC-E-9-1.25BA	CPA	2-7/8	4970	29.26	29.35	S
Avg						28.23	
8	8VC-E-9-1.25A	CPA	3-1/16	4710	27.25	28.08	S
9	8VC-E-9-1.25A	CPA	3-1/8	5360	28.46	27.49	S
10	8VC-E-9-1.25A	CPA	3	4970	26.84	26.92	S
Avg						27.49	
8	8VC-E-9-1.25V	TCA	2-7/8	4710	23.86	24.58	S/Cone
9	8VC-E-9-1.25V	TCA	2-15/16	5360	23.07	22.28	S
10	8VC-E-9-1.25V	TCA	2-15/16	4970	23.34	23.41	S
Avg						23.43	
8	8VC-E-9-1.25BW	TCA	3	4710	15.47	15.94	S
9	8VC-E-9-1.25BW	TCA	3-1/8	5360	18.11	17.49	S
10	8VC-E-9-1.25BW	TCA	3-1/16	4970	16.41	16.46	IGC/S
Avg						16.63	

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
8	8VC-E-9-1.25BA	TCA	2-15/16	4710	15.81	16.29	S/Cone
9	8VC-E-9-1.25BA	TCA	2-7/8	5360	11.55	11.16	IGC/Cone
10	8VC-E-9-1.25BA	TCA	3-1/16	4970	16.34	16.39	IGC/S
Avg						14.61	
8	8VC-E-9-1.25A	TCA	3	4710	19.86	20.46	IGC/S
9	8VC-E-9-1.25A	TCA	3	5360	16.57	16.00	IGC/Cone
10	8VC-E-9-1.25A	TCA	3	4970	13.77	13.81	IGC/T
Avg						16.76	
8	8VC-M-9-1.25	CIP	3-1/16	4710	27.14	27.96	S
9	8VC-M-9-1.25	CIP	3-1/16	5360	27.45	26.51	S
10	8VC-M-9-1.25	CIP	3-1/16	4970	28.78	28.87	S
Avg						27.78	
8	8VC-E-9-1.25	CIP	3	4710	26.89	27.71	S
9	8VC-E-9-1.25	CIP	3	5360	27.18	26.25	S
10	8VC-E-9-1.25	CIP	3-1/16	4970	24.02	24.09	S
Avg						26.02	
			Group 11				
11	5VC-E-6-13/16BA	CPA-1CPS	2-7/8	5230	15.61	15.26	S
11	5VC-E-6-13/16BA	CPA-1CPS	2-15/16	5230	13.60	13.30	IGC/S
11	5VC-E-6-13/16BA	CPA-1CPS	3-1/16	5230	11.35	11.10	IGC
Avg						13.22	
11	5VC-E-6-13/16BA	CPA-2CPS	2-7/8	5230	15.33	14.99	S
11	5VC-E-6-13/16BA	CPA-2CPS	3	5230	14.08	13.77	S/Cone
11	5VC-E-6-13/16BA	CPA-2CPS	3-1/8	5230	14.23	13.91	S/Cone
Avg						14.22	
11	5VC-E-6-13/16BA	CPA-1CPE	3-1/16	5230	17.20	16.82	S
11	5VC-E-6-13/16BA	CPA-1CPE	3-1/16	5230	16.72	16.35	S
11	5VC-E-6-13/16BA	CPA-1CPE	2-15/16	5230	13.33	13.03	S
Avg						15.40	
11	5VC-E-6-13/16BA	CPA-2CPE	2-7/8	5230	14.83	14.50	S
11	5VC-E-6-13/16BA	CPA-2CPE	3	5230	14.65	14.32	S
11	5VC-E-6-13/16BA	CPA-2CPE	3-1/8	5230	14.44	14.12	S
Avg						14.31	
11	5VC-E-6-7/8V	TCA	2-15/16	5230	9.86	9.64	IGC
11	5VC-E-6-7/8V	TCA	3	5230	12.28	12.01	IGC/S/Cone
11	5VC-E-6-7/8V	TCA	3-3/16	5230	11.86	11.60	IGC/S
Avg						11.08	
11	5VC-E-6-7/8BA	TCA	3-1/16	5230	6.86	6.71	IGC
11	5VC-E-6-7/8BA	TCA	3	5230	13.09	12.80	IGC/S/Cone

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
11	5VC-E-6-7/8BA	TCA	3-1/8	5230	10.73	10.49	IGC/S
Avg						10.00	
			Groups 12, 13 and 14				
12	8VC-E-6-1.25BA	TCB	2-7/8	5270	17.69	17.23	S
13	8VC-E-6-1.25BA	TCB	2-15/16	5600	16.97	16.04	S
14	8VC-E-6-1.25BA	TCB	3-1/8	4550	18.33	19.22	S
Avg						17.50	
12	8VC-E-9-1.25BA	TCB	3-1/8	5270	24.59	23.95	S
13	8VC-E-9-1.25BA	TCB	2-15/16	5600	23.69	22.38	S
14	8VC-E-9-1.25BA	TCB	2-3/4	4550	22.76	23.86	S
Avg						23.40	
12	8VC-E-12-1.25BA	TCB	3	5270	28.59	27.85	S
13	8VC-E-12-1.25BA	TCB	2-7/8	5600	31.56	29.82	S
14	8VC-E-12-1.25BA	TCB	3	4550	33.34	34.95	S
Avg						30.87	
12	8VC-E-15-1.25BA	TCB	2-13/16	5270	34.78	33.88	S
13	8VC-E-15-1.25BA	TCB	3-1/16	5600	42.03	39.71	S
14	8VC-E-15-1.25BA	TCB	3-1/8	4550	40.63	42.59	S
Avg						38.73	
12	8VC-E-6-1.25BA	TCA	2-7/8	5270	13.57	13.22	IGC/S
13	8VC-E-6-1.25BA	TCA	3-1/4	5600	14.16	13.38	IGC/S
14	8VC-E-6-1.25BA	TCA	3	4550	11.69	12.25	IGC/Cone
Avg						12.95	
12	8VC-E-9-1.25BA	TCA	2-3/4	5270	17.98	17.51	S
13	8VC-E-9-1.25BA	TCA	3	5600	13.53	12.78	IGC/T/S
14	8VC-E-9-1.25BA	TCA	3	4550	20.71	21.71	IGC/T/Cone
Avg						17.33	
12	8VC-E-12-1.25BA	TCA	3-1/8	5270	24.07	23.45	IGC/S/T
13	8VC-E-12-1.25BA	TCA	3	5600	25.75	24.33	IGC/Cone
Avg						23.89	
12	8VC-E-13-1.25BA	TCA	3-1/16	5270	28.23	27.50	IGC/S/T
13	8VC-E-15-1.25BA	TCA	3	5600	31.41	29.68	IGC/S/Cone
14	8VC-E-15-1.25BA	TCA	3	4550	32.96	34.55	IGC/S/Cone
Avg						32.11	
12	8VC-M-6-1.25	CIP	3-1/16	5270	18.09	17.62	S
13	8VC-M-6-1.25	CIP	3	5600	18.57	17.55	S
14	8VC-M-6-1.25	CIP	3-1/8	4550	17.33	18.17	S
Avg						17.78	

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
12	8VC-M-9-1.25	CIP	3-1/16	5270	29.50	28.73	S
13	8VC-M-9-1.25	CIP	3	5600	28.97	27.37	S
14	8VC-M-9-1.25	CIP	3-1/16	4550	28.17	29.53	S
Avg						28.54	
12	8VC-M-12-1.25	CIP	3	5270	38.20	37.21	S
13	8VC-M-12-1.25	CIP	3	5600	35.67	33.70	S
14	8VC-M-12-1.25	CIP	3-1/16	4550	36.86	38.64	S
Avg						36.52	
12	8VC-M-15-1.25	CIP	3-1/16	5270	45.04	43.87	S
13	8VC-M-15-1.25	CIP	3-1/16	5600	47.67	45.04	S
14	8VC-M-15-1.25	CIP	3	4550	44.96	47.13	S
Avg						45.35	
12	8VC-E-6-1.25	CIP	3-1/8	5270	16.53	16.10	S
13	8VC-E-6-1.25	CIP	3	5600	15.67	14.81	S
14	8VC-E-6-1.25	CIP	3-1/16	4550	16.42	17.21	S
Avg						16.04	
12	8VC-E-9-1.25	CIP	3	5270	25.20	24.55	S
13	8VC-E-9-1.25	CIP	3	5600	24.45	23.10	S
14	8VC-E-9-1.25	CIP	3	4550	24.31	25.48	S
Avg						24.38	
12	8VC-E-12-1.25	CIP	3-1/16	5270	34.47	33.58	S
13	8VC-E-12-1.25	CIP	3	5600	30.18	28.52	S
14	8VC-E-12-1.25	CIP	3-1/8	4550	30.04	31.49	S
Avg						31.20	
12	8VC-E-15-1.25	CIP	3	5270	43.58	42.45	S
13	8VC-E-15-1.25	CIP	3	5600	39.11	36.96	S
14	8VC-E-15-1.25	CIP	3-1/16	4550	35.98	37.72	S
Avg						39.04	
			Groups 15, 16 and 17				
15	5VC-E-4-7/8BA	TCB	3	5480	10.11	9.66	S
16	5VC-E-4-7/8BA	TCB	2-15/16	4610	9.72	10.12	S
17	5VC-E-4-7/8BA	TCB	3-1/16	4980	9.34	9.36	S
Avg						9.71	
15	5VC-E-6-7/8BA	TCB	2-7/8	5360	15.00	14.49	S/Cone
16	5VC-E-6-7/8BA	TCB	2-7/8	4610	15.06	15.68	S
17	5VC-E-6-7/8BA	TCB	2-7/8	4980	14.24	14.27	S/Cone
Avg						14.81	
15	5VC-E-9-7/8BA	TCB	2-7/8	5360	18.36	17.73	S/Cone
16	5VC-E-9-7/8BA	TCB	3-1/16	4610	22.86	23.81	S/Cone

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
17	5VC-E-9-7/8BA	TCB	2-7/8	4980	21.06	21.10	S/Cone
Avg						20.88	
15	5VC-E-12-7/8BA	TCB	2-13/16	5360	26.92	26.00	Cone
16	5VC-E-12-7/8BA	TCB	2-7/8	4610	28.23	29.40	IGC/S/Cone
17	5VC-E-12-7/8BA	TCB	2-3/4	4980	25.92	25.97	S/Cone
Avg						27.12	
15	5VS-E-4-7/8BA	TCB	3	5480	9.13	8.72	S
16	5VS-E-4-7/8BA	TCB	2-13/16	4610	8.81	9.18	S/Cone
17	5VS-E-4-7/8BA	TCB	2-7/8	4980	8.91	8.93	S/Cone
Avg						8.94	
15	5VS-E-6-7/8BA	TCB	2-3/4	5870	15.32	14.14	S
16	5VS-E-6-7/8BA	TCB	3-1/8	4610	11.94	12.43	S/Cone
17	5VS-E-6-7/8BA	TCB	3-1/16	4980	13.75	13.78	S/Cone
Avg						13.45	
15	5VS-E-9-7/8BA	TCB	2-3/4	5870	21.10	19.47	S/Cone
16	5VS-E-9-7/8BA	TCB	3	4610	21.34	22.22	S/Cone
17	5VS-E-9-7/8BA	TCB	2-15/16	4980	21.24	21.28	S/Cone
Avg						20.99	
15	5VS-E-12-7/8BA	TCB	2-7/8	5480	29.51	28.19	S/Cone
16	5VS-E-12-7/8BA	TCB	2-13/16	4610	25.17	26.21	S/Cone
17	5VS-E-12-7/8BA	TCB	3-1/16	4980	22.76	22.81	S/Cone
Avg						25.74	
15	5VC-E-4-7/8BA	TCA	2-15/16	5870	7.74	7.14	Cone
16	5VC-E-4-7/8BA	TCA	2-7/8	4610	7.34	7.64	Cone
17	5VC-E-4-7/8BA	TCA	3-1/16	4980	6.82	6.83	IGC/Cone
Avg						7.21	
15	5VC-E-6-7/8BA	TCA	3	5870	11.69	10.79	IGC/Cone
16	5VC-E-6-7/8BA	TCA	2-15/16	4610	11.79	12.28	IGC/Cone
17	5VC-E-6-7/8BA	TCA	2-7/8	4980	8.11	8.13	IGC/Cone
Avg						10.40	
15	5VC-E-9-7/8BA	TCA	2-3/4	5870	14.20	13.11	Cone
16	5VC-E-9-7/8BA	TCA	2-1/2	4610	16.02	16.68	IGC/Cone
17	5VC-E-9-7/8BA	TCA	2-7/8	4980	15.67	15.70	IGC/Cone
Avg						15.16	
15	5VC-E-12-7/8BA	TCA	2-15/16	5870	19.80	18.27	IGC/Cone
16	5VC-E-12-7/8BA	TCA	3-1/16	4610	23.17	24.13	S/Cone
17	5VC-E-12-7/8BA	TCA	3	4980	24.15	24.20	IGC/Cone
Avg						22.20	
15	5VC-M-4	CIP	3-1/4	5360	10.12	9.77	S/Cone
16	5VC-M-4	CIP	3	4610	9.37	9.76	S

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength *** kips	Failure mode****
17	5VC-M-4	CIP	3-1/16	4980	10.21	10.23	S
Avg						9.92	
15	5VC-M-6	CIP	3	5360	15.68	15.14	S/Cone
16	5VC-M-6	CIP	3	4610	15.35	15.99	S
17	5VC-M-6	CIP	3-1/16	4980	16.38	16.41	S
Avg						15.85	
15	5VC-M-9	CIP	3	5360	22.14	21.38	Pullout
16	5VC-M-9	CIP	3	4610	25.11	26.15	Cone
17	5VC-M-9	CIP	3	4980	22.74	22.79	S
Avg						23.44	
15	5VC-M-12	CIP	3	5360	26.99	26.07	Cone
16	5VC-M-12	CIP	3	4610	24.62	25.64	Cone
17	5VC-M-12	CIP	3	4980	28.09	28.15	S/Cone
Avg						26.62	
15	5VC-E-4	CIP	3	5480	9.29	8.87	S
16	5VC-E-4	CIP	3	4610	10.41	10.84	S
17	5VC-E-4	CIP	3	4980	9.42	9.44	S
Avg						9.72	
15	5VC-E-6	CIP	3-1/16	5480	15.82	15.11	S
16	5VC-E-6	CIP	3-1/16	4610	14.20	14.79	S
17	5VC-E-6	CIP	2-15/16	4980	15.30	15.33	S
Avg						15.08	
15	5VC-E-9	CIP	3-1/16	5480	23.18	22.14	S
16	5VC-E-9	CIP	3-1/16	4610	21.09	21.96	S
17	5VC-E-9	CIP	3	4980	23.03	23.08	S
Avg						22.40	
15	5VC-E-12	CIP	3	5480	28.88	27.59	S/Cone
16	5VC-E-12	CIP	3-1/16	4610	30.26	31.51	S/Cone
17	5VC-E-12	CIP	3	4980	29.78	29.84	Cone
Avg						29.65	
15	5VS-E-4	CIP	3	5870	8.72	8.05	S/Cone
16	5VS-E-4	CIP	3	4610	9.04	9.41	S
17	5VS-E-4	CIP	3	4980	8.74	8.76	S
Avg						8.74	
15	5VS-E-6	CIP	3-1/8	5870	14.73	13.59	S
16	5VS-E-6	CIP	3	4610	13.23	13.78	S
17	5VS-E-6	CIP	3-1/16	4980	14.57	14.60	S
Avg						13.99	
15	5VS-E-9	CIP	3-1/8	5870	23.38	21.58	S
16	5VS-E-9	CIP	3	4610	19.46	20.27	S

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
17	5VS-E-9	CIP	3	4980	21.55	21.59	S/Cone
Avg						21.15	
15	5VS-E-12	CIP	3	5870	25.50	23.53	Pullout
16	5VS-E-12	CIP	3-1/16	4610	27.59	28.73	S
17	5VS-E-12	CIP	3-1/16	4980	26.61	26.66	S/Cone
Avg						26.31	
			Groups 18 and 20				
18	8HC-T-E-6-1.25BA	NSA	2-15/16	5400	12.96	12.47	T
18	8HC-T-E-9-1.25BA	NSA	3-1/16	5400	18.68	17.97	S
18	8HC-T-E-12-1.25B	NSA	3	5400	29.78	28.66	S
18	8HC-T-E-6-1.25BA	CPA	3	5400	19.60	18.86	S
20	8HC-T-E-6-1.25BA	CPA	2-15/16	5230	15.53	15.18	S
Avg						17.02	
18	8HC-T-E-9-1.25BA	CPA	3-1/16	5400	28.23	27.16	S
20	8HC-T-E-9-1.25BA	CPA	3	5230	29.25	28.6	S
Avg						27.88	
18	8HC-T-E-12-1.25B	CPA	2-15/16	5400	35.64	34.29	S
20	8HC-T-E-12-1.25B	CPA	2-13/16	5230	31.09	30.4	S
Avg						32.35	
20	8HC-T-E-15-1.25B	CPA	2-7/8	5230	35	34.22	Pullout
20	8HC-T-E-15-1.25B	CPA	3-1/16	5230	46.75	45.71	S
Avg						39.97	
18	8HC-T-E-6-1.25BA	TCA	2-15/16	5400	17.64	16.97	IGC/S
20	8HC-T-E-6-1.25BA	TCA	3	5230	11.61	11.35	IGC/T
Avg						14.16	
18	8HC-T-E-9-1.25BA	TCA	2-3/4	5400	17.02	16.38	S
20	8HC-T-E-9-1.25BA	TCA	3-1/16	5230	18.43	18.02	IGC/T
Avg						17.2	
18	8HC-T-E-12-1.25B	TCA	2-15/16	5400	30.42	29.27	S/Cone
20	8HC-T-E-15-1.25B	TCA	2-15/16	5230	31.15	30.46	IGC/S
20	8HC-T-E-15-1.25B	TCA	3-1/8	5230	31.52	30.87	IGC/T
Avg						30.67	
18	8HC-T-E-9	CIP	3	5400	25.58	24.61	S
18	8HC-T-E-9	CIP	3-1/8	5400	27.38	26.35	S
18	8HC-T-E-9	CIP	3-3/16	5400	27.89	26.84	S
Avg						25.93	
20	8HC-T-E-12	CIP	3-1/16	5230	29.87	29.21	S
20	8HC-T-E-15	CIP	3-1/4	5230	41.55	40.63	S

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
18	8HC-B-E-6-1.25BA	NSA	2-7/8	5400	11.01	10.59	T
18	8HC-B-E-9-1.25BA	NSA	3-1/4	5400	24.59	23.66	Pullout
18	8HC-B-E-12-1.25B	NSA	3-1/16	5400	32.48	31.25	S
18	8HC-B-E-6-1.25BA	CPA	2-3/4	5400	20.32	19.55	S
20	8HC-T-E-6-1.25BA	CPA	3-1/4	5230	18.73	18.31	S
Avg						18.93	
18	8HC-B-E-9-1.25BA	CPA	3-1/16	5400	31.67	30.47	S
20	8HC-T-E-9-1.25BA	CPA	3	5230	31.05	30.36	S
Avg						30.42	
18	8HC-B-E-12-1.25B	CPA	3	5400	40.14	38.62	S
20	8HC-T-E-12-1.25B	CPA	3-1/16	5230	35.2	34.91	Pullout
Avg						36.77	
20	8HC-T-E-15-1.25B	CPA	3	5230	43.49	42.52	Pullout
20	8HC-T-E-15-1.25B	CPA	3-1/16	5230	42.51	41.56	Pullout
Avg						42.04	
18	8HC-B-E-6-1.25BA	TCA	2-7/8	5400	11.15	10.73	T
20	8HC-T-E-6-1.25BA	TCA	3-1/16	5230	14.37	14.05	IGC/Cone
Avg						12.39	
18	8HC-B-E-9-1.25BA	TCA	2-3/4	5400	19.92	19.17	IGC/S/Cone
20	8HC-B-E-9-1.25BA	TCA	3	5230	18.36	17.95	IGC
Avg						18.56	
18	8HC-B-E-12-1.25B	TCA	3-1/16	5400	28.78	27.69	IGC/Cone
20	8HC-B-E-12-1.25B	TCA	2-15/16	5230	28.45	22.82	IGC/Cone
Avg						25.26	
20	8HC-B-E-13-1.25B	TCA	2-7/8	5230	27.54	26.92	IGC/S
20	8HC-B-E-15-1.25B	TCA	2-13/16	5230	32.65	31.92	IGC/T
18	8HC-B-E-6	CIP	3-3/16	5400	30.75	29.59	S
18	8HC-B-E-9	CIP	2-3/4	5400	28.51	27.43	S
18	8HC-B-E-12	CIP	2-7/8	5400	29.05	27.95	S
20	8HC-B-E-12	CIP	3-1/8	5230	31.72	31.01	S
Avg						29.48	
20	8HC-B-E-15	CIP	2-4/5	5230	45.28	44.22	T

Group 19

19	5VC-E-6-7/8BA	TCB	1-1/2	3960	10.70	12.02	S
19	5VC-E-6-7/8BA	TCB	1-7/16	3960	10.88	12.23	T
Avg						12.13	

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
19	5VC-E-9-7/8BA	TCB	1-3/8	3960	18.02	20.25	S
19	5VC-E-9-7/8BA	TCB	1-1/2	3960	19.16	21.53	T
Avg						20.89	
19	5VC-E-12-7/8BA	TCB	1-3/8	3960	22.84	25.66	T
19	5VC-E-12-7/8BA	TCB	1-1/2	3960	20.85	23.43	Pullout
Avg						24.55	
19	5VC-E-6-7/8BA	TCA	1-1/2	3960	6.99	7.85	IGC
19	5VC-E-6-7/8BA	TCA	1-7/16	3960	4.62	5.19	IGC/Cone
Avg						6.52	
19	5VC-E-9-7/8BA	TCA	1-1/2	3960	11.90	13.37	IGC/Cone
19	5VC-E-9-7/8BA	TCA	1-3/8	3960	10.48	11.78	IGC/Cone
Avg						12.58	
19	5VC-E-12-7/8BA	TCA	1-1/2	3960	15.68	17.62	IGC/Cone
19	5VC-E-12-7/8BA	TCA	1-5/8	3960	14.62	16.43	IGC/Cone
Avg						17.03	
19	5VC-M-6	CIP	1-9/16	3960	11.64	13.08	T
19	5VC-M-6	CIP	1-7/8	3960	11.50	12.92	T
Avg						13.00	
19	5VC-M-9	CIP	1/9/16	3960	16.19	18.19	T
19	5VC-M-9	CIP	1-7/16	3960	20.46	22.99	T
Avg						20.59	
19	5VC-M-12	CIP	1-1/2	3960	25.16	28.27	T
19	5VC-M-12	CIP	1-1/2	3960	23.96	26.92	S
Avg						27.60	
19	5VC-E-6	CIP	1-1/2	3960	11.08	12.45	T
19	5VC-E-6	CIP	1-1/2	3960	10.56	11.87	S
Avg						12.16	
19	5VC-E-9	CIP	1-1/2	3960	17.11	19.23	S
19	5VC-E-9	CIP	1-9/16	3960	15.93	17.90	S
Avg						18.57	
19	5VC-E-12	CIP	1-1/2	3960	22.66	25.46	S
19	5VC-E-12	CIP	1-1/2	3960	22.74	25.55	S
Avg						25.51	
			Group 21				
21	5HC-T-E-4-7/8BA	CPA	2-15/16	4410	7.63	8.12	Pullout
21	5HC-T-E-6-7/8BA	CPA	3-1/8	4410	9.25	9.85	Pullout
21	5HC-T-E-9-7/8BA	CPA	2-15/16	4670	3.53	3.65	Pullout
21	5HC-T-E-12-7/8B/	CPA	3	4410	1.50	1.60	Pullout
21	5HC-T-E-4-7/8BA	TCA	2-15/16	4410	8.41	8.95	IGC/S/Cone

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
21	5HC-T-E-6-7/8BA	TCA	3	4410	13.01	13.85	IGC/Cone
21	5HC-T-E-9-7/8BA	TCA	3	4670	14.18	14.67	IGC/Cone
21	5HC-T-E-12-7/8B/	TCA	3-5/8	4410	19.14	20.38	Cone
21	5HC-T-E-4	CIP	3	4670	9.26	9.58	S
21	5HC-T-E-6	CIP	3	4670	14.13	14.62	S/Cone
21	5HC-T-E-9	CIP	3-1/16	4410	22.17	23.61	S/Cone
21	5HC-T-E-12	CIP	3-1/16	4410	26.6	28.32	T
21	5HC-B-E-4-7/8BA	CPA	3	4410	7.14	7.60	Pullout
21	5HC-B-E-6-7/8BA	CPA	3	4410	7.2	7.67	Pullout
21	5HC-B-E-9-7/8BA	CPA	3	4670	6.41	6.63	Pullout
21	5HC-B-E-12-7/8B/	CPA	3	4410	4.18	4.45	Pullout
21	5HC-B-E-4-7/8BA	TCA	2-7/8	4410	8.04	8.56	IGC/Cone
21	5HC-B-E-6-7/8BA	TCA	2-7/8	4410	13.6	14.48	Pullout
21	5HC-B-E-9-7/8BA	TCA	3	4670	12.97	13.42	IGC/Cone
21	5HC-B-E-12-7/8B/	TCA	3	4410	20.25	21.56	Cone
21	5HC-B-E-4	CIP	2-7/8	4670	9.23	9.55	S
21	5HC-B-E-6	CIP	3-1/8	4670	14.74	15.25	S
21	5HC-B-E-9	CIP	2-7/8	4410	23.06	24.55	S/Cone
21	5HC-B-E-12	CIP	3	4410	28.39	30.23	T
21	5VC-E-6-7/8BA	TCB-NTR	2-15/16	5270	14.54	14.16	IGC/T/Cone
21	5VC-E-6-7/8BA	TCB-NTR	2-15/16	5270	15.17	14.78	IGC/T/Cone
Avg						14.47	
21	5VC-E-9-7/8BA	TCB-NTR	2-7/8	5270	19.89	19.37	S/T
21	5VC-E-9-7/8BA	TCB-NTR	3-1/16	5270	24.01	23.39	IGC/S/Cone
Avg						21.38	
21	5VC-E-12-7/8BA	TCB-NTR	3-1/16	5270	28.00	27.27	IGC/T
21	5VC-E-12-7/8BA	TCB-NTR	2-15/16	5270	27.27	26.56	IGC/T/Cone
Avg						26.92	
			Group 22				
22	5VC-E-6-7/8BA	TCB	3	4980	16.57	16.60	S
22	5VC-E-6-7/8BA	TCB	3-1/8	4980	17.37	17.40	S
Avg						17.00	
22	5VC-E-9-7/8BA	TCB	2-3/4	4980	21.61	21.65	S
22	5VC-E-9-7/8BA	TCB	3	4980	26.54	26.59	S/Cone
Avg						24.12	
22	5VC-E-12-7/8BA	TCB	3-1/16	4980	24.11	24.16	T
22	5VC-E-12-7/8BA	TCB	3	4980	25.88	25.93	T
Avg						25.05	

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
22	5VC-E-6-7/8BA	TCA	2-15/16	4980	11.97	11.99	IGC/Cone
22	5VC-E-6-7/8BA	TCA	2-15/16	4980	13.42	13.45	IGC/Cone
Avg						12.72	
22	5VC-E-9-7/8BA	TCA	2-15/16	4980	18.32	18.36	IGC/Cone
22	5VC-E-9-7/8BA	TCA	3-1/16	4980	18.97	19.01	IGC/Cone
Avg						18.68	
22	5VC-E-12-7/8BA	TCA	2-15/16	4980	20.61	20.65	IGC/T
22	5VC-E-12-7/8BA	TCA	3-1/8	4980	22.85	22.90	IGC
Avg						21.77	
22	5VC-E-6-7/8BA	TCB	1-9/16	4980	13.64	13.67	T
22	5VC-E-6-7/8BA	TCB	1-1/2	4980	11.62	11.64	S/T
Avg						12.66	
22	5VC-E-9-7/8BA	TCB	1-9/16	4980	19.00	19.04	S
22	5VC-E-9-7/8BA	TCB	1-1/2	4980	19.01	19.05	T
Avg						19.04	
22	5VC-E-12-7/8BA	TCB	1-9/16	4980	24.06	24.11	S/Cone
22	5VC-E-12-7/8BA	TCB	1-1/2	4980	23.26	23.31	S/T
Avg						23.71	
22	5VC-E-6-7/8BA	TCA	1-1/2	4980	7.59	7.59	T/Cone
22	5VC-E-6-7/8BA	TCA	1-5/8	4980	10.17	10.19	IGC/Cone
Avg						8.89	
22	5VC-E-9-7/8BA	TCA	1-5/8	4980	15.68	15.71	IGC/Cone
22	5VC-E-9-7/8BA	TCA	1-3/8	4980	12.47	12.50	S/T/Cone
Avg						14.10	
22	5VC-E-12-7/8BA	TCA	1-5/8	4980	14.94	14.97	IGC/Cone
22	5VC-E-12-7/8BA	TCA	1-3/4	4980	17.88	17.92	IGC/T
Avg						16.44	
			Group 23				
23	5VC-E-6-7/8BA	NSA	2-3/4	2700	10.90	14.83	S
23	5VC-E-6-7/8BA	NSA	2-13/16	2700	9.61	13.08	T
23	5VC-E-6-7/8BA	NSA	2-15/16	2700	11.17	15.20	S
23	Avg					14.37	
23	5VC-E-6-7/8BA	CPA	2-15/16	2700	9.93	13.51	Pullout
23	5VC-E-6-7/8BA	CPA	3-1/16	2700	7.73	10.52	Pullout
23	5VC-E-6-7/8BA	CPA	2-15/16	2700	5.13	6.98	Pullout
23	Avg					10.34	
23	5VC-E-6-7/8BA	TCA	3	2700	8.64	11.76	IGC/Cone
23	5VC-E-6-7/8BA	TCA	3-3/16	2700	9.03	12.29	IGC/Cone
23	5VC-E-6-7/8BA	TCA	3-3/16	2700	6.41	8.72	IGC/T/Cone

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
23	Avg					10.92	
			Group 24				
24	8HC-T-E-6-1.25BA	NSA-NTR	2-7/8	4980	13.39	13.42	S
24	8HC-T-3-9-1.25BA	NSA-NTR	2-15/16	4980	22.98	23.03	S
24	8HC-T-E-12-1.25B	NSA-NTR	3-1/8	4980	27.63	27.69	S
24	8HC-T-E-6-1.25BA	CPA-NTR	2-7/8	4980	15.67	15.70	S/T
24	8HC-T-E-9-1.25BA	CPA-NTR	2-7/8	4980	25.19	25.24	S/T
24	8HC-T-E-12-1.25B	CPA-NTR	2-7/8	4980	37.67	37.75	T
24	8HC-T-E-15-1.25B	CPA-NTR	2-3/4	4980	39.65	39.43	S
24	8HC-T-E-6-1.25BA	TCA-NTR	2-3/4	4980	11.37	11.39	IGC/S
24	8HC-T-E-9-1.25BA	TCA-NTR	3	4980	17.56	17.60	IGC/S/Cone
24	8HC-T-E-12-1.25B	TCA-NTR	2-11/16	4980	22.25	22.29	IGC/Cone
24	8HC-T-E-15-1.25B	TCA-NTR	3-1/8	4980	38.17	38.25	T/Cone
24	8HC-B-E-6-1.25BA	NSA-NTR	2-7/8	4980	15.15	15.18	S
24	8HC-B-E-9-1.25BA	NSA-NTR	3-1/8	4980	21.79	21.83	S
24	8HC-B-E-12-1.25B	NSA-NTR	3-1/8	4980	31.52	31.58	S
24	8HC-B-E-15-1.25B	NSA-NTR	3-1/8	4980	36.68	36.75	S
24	8HC-B-E-6-1.25BA	TCA-NTR	3-1/8	4980	14.06	14.09	IGC/Cone
24	8HC-B-E-6-1.25BA	TCA-NTR	3	4980	12.27	12.29	S/T/Cone
Avg						13.19	
24	8HC-B-E-9-1.25BA	TCA-NTR	3	4980	20.88	20.92	IGC/Cone
24	8HC-B-E-12-1.25B	TCA-NTR	3	4980	30.73	30.79	IGC/Cone
24	8HC-B-E-12-1.25B	TCA-NTR	3-1/16	4980	25.40	25.45	IGC/Cone
Avg						28.12	
24	8HC-B-E-15-1.25B	TCA-NTR	3-1/16	4980	34.33	34.40	S/Cone
24	5VC-E-9-7/8BA	NSA-1:3	3-1/16	4740	23.35	23.98	Cone
24	5VC-E-12-7/8BA	NSA-1:3	2-3/4	4980	28.35	28.41	S/Cone
24	5VC-E-12-7/8BA	TCB-1:3	2-13/16	4980	30.08	30.14	S/T
24	5VC-E-6-7/8BA	CPA-1:3	3	4740	7.68	7.89	Pullout
24	5VC-E-9-7/8BA	CPA-1:3	2-3/4	4740	8.10	8.32	Pullout
24	5VC-E-12-7/8BA	CPA-1:3	3-1/8	4980	6.25	6.26	Pullout
24	5VC-E-6-7/8BA	NSA-1:6	2-15/16	4600	9.17	9.56	S/T
24	5VC-E-6-7/8BA	NSA-1:6	3	4600	5.00	5.21	S/T
Avg						7.39	

Table 2.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
24	5VC-E-12-7/8BA	NSA-1:6	2-13/16	4740	33.52	34.43	S/T##
24	5VC-E-6-7/8BA	TCB-1:6	2-5/8	4600	13.35	13.92	T
24	5VC-E-9-7/8BA	TCB-1:6	2-7/8	4740	18.90	19.41	S/Cone
24	5VC-E-12-7/8BA	TCB-1:6	3-1/8	4740	30.03	30.84	Cone##
24	5VC-E-9-7/8BA	CPA-1:6	2-15/16	4600	8.14	8.49	Pullout
24	5VC-E-9-7/8BA	CPA-1:6	3-1/8	4600	9.40	9.80	Pullout
Avg						9.15	
24	5VC-E-12-7/8BA	CPA-1:6	2-7/8	4740	10.99	11.29	Pullout

##Rebar failed in tension also

* Specimen Label: #ab-c-def or #ab-L-c-def

# = Bar Size, No. 5 or No. 8
a = Bar Orientation, H - horizontal or V - vertical
b = Bar Pattern, C or S
c = Bar Surface, M - small scale (uncoated), E - epoxy-coated
d = Embedment length, in.
e = Hole diameter, in.
f = Cleaning method, V - vacuum drilled, A - air, BA - brush with air, BW - brush with water
L = Level of Placement for horizontal bars, B - bottom-cast or T - top-cast

** Anchorage Method:

CIP = Cast-in-place;
CPA = Capsule A;
CPB = Capsule B;
TCA = Two-component grout A;
TCB = Two-compontent grout B;
NSA = Nonshrink grout A;
NSB = Nonshrink grout B;
1CPS = One capsule with standard number of rotations
2CPS = Two capsules with standard number of rotations
1CPE = One capsule with extra rotations
2CPE = Two capsules with extra rotations
NTR = No parallel tensile reinforcement
1:3 and 1:6 = Change in cover: change in embedded length for sloped bars

*** Mod. bond strength = (Bond strength) $(5000/f'_c)^{.5}$

**** Failure Mode: S = Splitting; T = Tensile; IGC = Interface between grout and concrete; Cone; Pullout. S, T and Cone failures were accompanied by a failure at the interface between the grout and the reinforcing bars (or between the concrete and the reinforcing bar in the case of cast-in-place bars) unless the failure mode includes an IGC designation

Table 3.1: Statistical Data for No. 5 Bars in Groups 4, 5 and 6.
Hole Cleaning Method: Brush with water, BW, except as noted

Bar Surface-Grout	Norm. Bond Str., kips Gp. 4	Gp. 5	Gp. 6	Mean Bond Str., Xm, kips	SUM (Xi-Xm)^2	No. of Tests	Std. Deviation
SMALL HOLE							
M-NSA	16.412	14.910	13.901	15.074	3.192	3	1.263
E-NSA	***	15.292	10.921	13.106	9.552	2	3.091
E-NSB	14.239	14.458	13.824	14.174	0.207	3	0.332
E-TCB	17.962	16.021	13.459	15.814	10.202	3	2.259
E-CPA	12.861	9.958	10.287	11.035	5.056	3	1.590
E-CPB	11.091	10.659	7.340	9.697	8.424	3	2.052
				SUM=	36.634		
				Std. Dev.=	1.825		
M-TCA	10.718	12.648	7.316	8.477	14.579	3	2.700
E-TCA	12.909	12.118	10.181	2.419	3.941	3	1.404
				SUM=	18.520		
				Std. Dev.=	2.152		
LARGE HOLE							
M-NSA	15.503	14.240	12.863	14.202	3.486	3	1.320
E-NSA	16.019	15.064	13.728	14.937	2.649	3	1.151
E-NSB	14.340	14.155	13.661	14.052	0.246	3	0.351
E-TCB	15.560	15.207	14.190	14.986	1.012	3	0.711
M-NSA*	17.024	14.676	14.324	15.341	4.309	3	1.468
M-NSA**	16.120	15.652	14.728	15.500	1.003	3	0.708
				SUM=	12.705		
				Std. Dev.=	1.029		
M-TCA	11.770	13.900	11.613	12.428	3.263	3	1.277
E-TCA	12.105	13.757	11.796	12.533	2.223	3	1.054
				SUM=	5.486		
				Std. Dev.=	1.171		

* Cleaning Method: Brush with Air, BA.

** Cleaning Method: Air, A.

*** Data not included because false reading was obtained due to rebar bending during test.

Table 3.2: Hypothesis Testing using Student t-Test for No. 5 Bars in Groups 4, 5 and 6.
Hole Cleaning Method: Brush with water, BW, except as noted.
Null Hypothesis, H0: Mean bond strength of population 1 = Mean bond strength of population 2

Bar Surface-Grout 1	Bar Surface-Grout 2	Mean Bond Str.,kips 1	Mean Bond Str.,kips 2	No. of Tests 1	No. of Tests 2	Std. Dev. 1	Std. Dev. 2	t(calc.)	$t(\alpha/2=0.10)=1.533$ H0 Rejected	$t(\alpha/2=0.05)=2.132$ H0 Rejected	$t(\alpha/2=0.025)=2.776$ H0 Rejected	$t(\alpha/2=0.01)=3.747$ H0 Rejected
SMALL HOLE												
M-NSA	E-NSA	15.07	13.11	3	2	1.26	3.09	1.047	NO	NO	NO	NO
M-NSA	E-NSB	15.07	14.17	3	3	1.26	0.33	1.198	NO	NO	NO	NO
M-NSA	M-TCA	15.07	10.23	3	3	1.26	2.70	2.817	YES	YES	YES	NO
M-NSA	E-TCA	15.07	11.74	3	3	1.26	1.40	3.063	YES	YES	YES	NO
M-NSA	E-TCB	15.07	15.81	3	3	1.26	2.26	-0.495	NO	NO	NO	NO
M-NSA	E-CPA	15.07	11.04	3	3	1.26	1.59	3.446	YES	YES	YES	NO
M-NSA	E-CPB	15.07	9.70	3	3	1.26	2.05	3.869	YES	YES	YES	YES
E-NSA	E-NSB	13.11	14.17	2	3	3.09	0.33	-0.644	NO	NO	NO	NO
E-NSA	M-TCA	13.11	10.23	2	3	3.09	2.70	1.112	NO	NO	NO	NO
E-NSA	E-TCA	13.11	11.74	2	3	3.09	1.40	0.708	NO	NO	NO	NO
E-NSA	E-TCB	13.11	15.81	2	3	3.09	2.26	-1.153	NO	NO	NO	NO
E-NSA	E-CPA	13.11	11.04	2	3	3.09	1.59	1.027	NO	NO	NO	NO
E-NSA	E-CPB	13.11	9.70	2	3	3.09	2.05	1.527	NO	NO	NO	NO
E-NSB	M-TCA	14.17	10.23	3	3	0.33	2.70	2.514	YES	YES	NO	NO
E-NSB	E-TCA	14.17	11.74	3	3	0.33	1.40	2.932	YES	YES	YES	NO
E-NSB	E-TCB	14.17	15.81	3	3	0.33	2.26	-1.245	NO	NO	NO	NO
E-NSB	E-CPA	14.17	11.04	3	3	0.33	1.59	3.351	YES	YES	YES	NO
E-NSB	E-CPB	14.17	9.70	3	3	0.33	2.05	3.737	YES	YES	YES	NO
M-TCA	E-TCA	10.23	11.74	3	3	2.70	1.40	-0.859	NO	NO	NO	NO
M-TCA	E-TCB	10.23	15.81	3	3	2.70	2.26	-2.749	YES	YES	NO	NO
M-TCA	E-CPA	10.23	11.04	3	3	2.70	1.59	-0.447	NO	NO	NO	NO
M-TCA	E-CPB	10.23	9.70	3	3	2.70	2.05	0.270	NO	NO	NO	NO
E-TCA	E-TCB	11.74	15.81	3	3	1.40	2.26	-2.656	YES	YES	NO	NO
E-TCA	E-CPA	11.74	11.04	3	3	1.40	1.59	0.572	NO	NO	NO	NO
E-TCA	E-CPB	11.74	9.70	3	3	1.40	2.05	1.421	NO	NO	NO	NO
E-TCB	E-CPA	15.81	11.04	3	3	2.26	1.59	2.997	YES	YES	YES	NO
E-TCB	E-CPB	15.81	9.70	3	3	2.26	2.05	3.473	YES	YES	YES	NO
E-CPA	E-CPB	11.04	9.70	3	3	1.59	2.05	0.893	NO	NO	NO	NO

Table 3.2 (continued)

Bar Surface-Grout 1	Bar Surface-Grout 2	Mean Bond Str.,kips 1	Mean Bond Str.,kips 2	No. of Tests 1	No. of Tests 2	Std. Dev. 1	Std. Dev. 2	t(calc.)	t ($\alpha/2$=0.10)=1.533 H0 Rejected	t ($\alpha/2$=0.05)=2.132 H0 Rejected	t ($\alpha/2$=0.025)=2.776 H0 Rejected	t ($\alpha/2$=0.01)=3.747 H0 Rejected
LARGE HOLE												
M-NSA	E-NSA	14.20	14.94	3	3	1.32	1.15	-0.727	NO	NO	NO	NO
M-NSA	E-NSB	14.20	14.05	3	3	1.32	0.35	0.192	NO	NO	NO	NO
M-NSA	M-TCA	14.20	12.43	3	3	1.32	1.28	1.740	YES	NO	NO	NO
M-NSA	E-TCA	14.20	12.55	3	3	1.32	1.05	1.691	YES	NO	NO	NO
M-NSA	E-TCB	14.20	14.99	3	3	1.32	0.71	-0.905	NO	NO	NO	NO
M-NSA	M-NSA*	14.20	15.34	3	3	1.32	1.47	-1.000	YES	NO	NO	NO
M-NSA	M-NSA**	14.20	15.50	3	3	1.32	0.71	-1.500	YES	NO	NO	NO
E-NSA	E-NSB	14.94	14.05	3	3	1.15	0.35	1.278	NO	NO	NO	NO
E-NSA	M-TCA	14.94	12.43	3	3	1.15	1.28	2.644	NO	YES	NO	NO
E-NSA	E-TCA	14.94	12.55	3	3	1.15	1.05	2.646	NO	YES	NO	NO
E-NSA	E-TCB	14.94	14.99	3	3	1.15	0.71	-0.062	NO	NO	NO	NO
E-NSA	M-NSA*	14.94	15.34	3	3	1.15	1.47	-0.375	NO	NO	NO	NO
E-NSA	M-NSA**	14.94	15.50	3	3	1.15	0.71	-0.720	NO	NO	NO	NO
E-NSB	M-TCA	14.05	12.43	3	3	0.35	1.28	2.295	YES	YES	NO	NO
E-NSB	E-TCA	14.05	12.55	3	3	0.35	1.05	2.336	YES	YES	NO	NO
E-NSB	E-TCB	14.05	14.99	3	3	0.35	0.71	-2.044	YES	NO	NO	NO
E-NSB	M-NSA*	14.05	15.34	3	3	0.35	1.47	-1.482	NO	NO	NO	NO
E-NSB	M-NSA**	14.05	15.50	3	3	0.35	0.71	-3.184	YES	YES	YES	NO
M-TCA	E-TCA	12.43	12.55	3	3	1.28	1.05	-0.137	NO	NO	NO	NO
M-TCA	E-TCB	12.43	14.99	3	3	1.28	0.71	-3.228	YES	YES	YES	NO
M-TCA	M-NSA*	12.43	15.34	3	3	1.28	1.47	-2.685	YES	YES	NO	NO
M-TCA	M-NSA**	12.43	15.50	3	3	1.28	0.71	-3.883	YES	YES	YES	YES
E-TCA	E-TCB	12.55	14.99	3	3	1.05	0.71	-3.313	YES	YES	YES	NO
E-TCA	M-NSA*	12.55	15.34	3	3	1.05	1.47	-2.673	YES	YES	NO	NO
E-TCA	M-NSA**	12.55	15.50	3	3	1.05	0.71	-4.021	YES	YES	YES	YES
E-TCB	M-NSA*	14.99	15.34	3	3	0.71	1.47	-0.378	NO	NO	NO	NO
E-TCB	M-NSA**	14.99	15.50	3	3	0.71	0.71	-0.886	NO	NO	NO	NO
M-NSA*	M-NSA**	15.34	15.50	3	3	1.47	0.71	-0.167	NO	NO	NO	NO

* Cleaning method: Brush with air, BA.

** Cleaning method: Air, A.

Table 3.2 (continued)

Bar Surface-Grout		Mean Bond Str., kips		No. of Tests		Std. Dev.		t(calc.)	t ($\alpha/2$=0.10)=1.533	t ($\alpha/2$=0.05)=2.132	t ($\alpha/2$=0.025)=2.776	t ($\alpha/2$=0.01)=3.747
1	2	1	2	1	2	1	2		H0 Rejected	H0 Rejected	H0 Rejected	H0 Rejected
SMALL HOLE VERSUS LARGE HOLE												
M-NSA	M-NSA	15.07	14.20	3	3	1.26	1.32	0.703	NO	NO	NO	NO
E-NSA	E-NSA	13.11	14.94	2	3	3.09	1.15	-0.994	NO	NO	NO	NO
E-NSB	E-NSB	14.17	14.06	3	3	0.33	0.35	0.622	NO	NO	NO	NO
M-TCA	M-TCA	10.23	12.43	3	3	2.70	1.28	-1.258	NO	NO	NO	NO
E-TCA	E-TCA	11.74	12.55	3	3	1.40	1.05	-0.790	NO	NO	NO	NO
E-TCB	E-TCB	15.81	14.99	3	3	2.05	0.71	0.620	NO	NO	NO	NO

Table 3.3: Hypothesis Testing using "z-test" for No. 5 Bars in Groups 4, 5 and 6.
Hole Cleaning Method: Brush with water, BW, except as noted.
Null Hypothesis, H0: Mean bond strength of population 1 = Mean bond strength of population 2

Bar Surface-Grout 1	Bar Surface-Grout 2	Mean Bond Str.,kips 1	Mean Bond Str.,kips 2	No. of Tests 1	No. of Tests 2	Std. Dev. 1	Std. Dev. 2	z(calc.)	$z (\alpha/2=0.10)=1.282$ H0 Rejected	$z (\alpha/2=0.05)=1.645$ H0 Rejected	$z (\alpha/2=0.025)=1.960$ H0 Rejected	$z (\alpha/2=0.01)=2.326$ H0 Rejected
SMALL HOLE												
M-NSA	E-NSA	15.07	13.11	3	2	1.83	1.83	1.181	NO	NO	NO	NO
M-NSA	E-NSB	15.07	14.17	3	3	1.83	1.83	0.604	NO	NO	NO	NO
M-NSA	M-TCA	15.07	10.23	3	3	1.83	2.15	2.975	YES	YES	YES	NO
M-NSA	E-TCA	15.07	11.74	3	3	1.83	2.15	2.049	YES	YES	YES	NO
M-NSA	E-TCB	15.07	15.81	3	3	1.83	1.83	-0.504	NO	NO	NO	NO
M-NSA	E-CPA	15.07	11.04	3	3	1.83	1.83	2.711	YES	YES	YES	YES
M-NSA	E-CPB	15.07	9.70	3	3	1.83	1.83	2.818	YES	YES	YES	YES
E-NSA	E-NSB	13.11	14.17	2	3	1.83	1.83	-0.641	NO	NO	NO	NO
E-NSA	M-TCA	13.11	10.23	2	3	1.83	2.15	1.607	YES	NO	NO	NO
E-NSA	E-TCA	13.11	11.74	2	3	1.83	2.15	0.765	NO	NO	NO	NO
E-NSA	E-TCB	13.11	15.81	2	3	1.83	1.83	-1.625	YES	NO	NO	NO
E-NSA	E-CPA	13.11	11.04	2	3	1.83	1.83	1.243	NO	NO	NO	NO
E-NSA	E-CPB	13.11	9.70	2	3	1.83	1.83	1.340	YES	NO	NO	NO
E-NSB	M-TCA	14.17	10.23	3	3	1.83	2.15	2.423	YES	YES	YES	YES
E-NSB	E-TCA	14.17	11.74	3	3	1.83	2.15	1.497	YES	NO	YES	NO
E-NSB	E-TCB	14.17	15.81	3	3	1.83	1.83	-1.101	NO	NO	NO	NO
E-NSB	E-CPA	14.17	11.04	3	3	1.83	1.83	2.107	YES	YES	YES	NO
E-NSB	E-CPB	14.17	9.70	3	3	1.83	1.83	2.214	YES	YES	YES	NO
M-TCA	E-TCA	10.23	11.74	3	3	2.15	2.15	-0.859	NO	NO	NO	NO
M-TCA	E-TCB	10.23	15.81	3	3	2.15	1.83	-3.430	YES	YES	YES	YES
M-TCA	E-CPA	10.23	11.04	3	3	2.15	1.83	-0.496	NO	NO	NO	NO
M-TCA	E-CPB	10.23	9.70	3	3	2.15	1.83	-0.398	NO	NO	NO	NO
E-TCA	E-TCB	11.74	15.81	3	3	2.15	1.83	-2.504	YES	YES	YES	YES
E-TCA	E-CPA	11.74	11.04	3	3	2.15	1.83	0.430	NO	NO	NO	NO
E-TCA	E-CPB	11.74	9.70	3	3	2.15	1.83	1.251	NO	NO	NO	NO
E-TCB	E-CPA	15.81	11.04	3	3	1.83	1.83	3.207	YES	YES	YES	YES
E-TCB	E-CPB	15.81	9.70	3	3	1.83	1.83	4.105	YES	YES	YES	YES
E-CPA	E-CPB	11.04	9.70	3	3	1.83	1.83	0.987	NO	NO	NO	NO

Table 3.3 (continued)

Bar Surface-Grout 1	Bar Surface-Grout 2	Mean Bond Str.,kips 1	Mean Bond Str.,kips 2	No. of Tests 1	No. of Tests 2	Std. Dev. 1	Std. Dev. 2	z(calc.)	z (α/2=0.10)=1.282 H0 Rejected	z (α/2=0.05)=1.645 H0 Rejected	z (α/2=0.025)=1.960 H0 Rejected	z (α/2=0.01)=2.326 H0 Rejected
LARGE HOLE												
M-NSA	E-NSA	14.20	14.94	3	3	1.03	1.03	-0.875	NO	NO	NO	NO
M-NSA	E-NSB	14.20	14.05	3	3	1.03	1.03	0.347	NO	NO	NO	NO
M-NSA	M-TCA	14.20	12.43	3	3	1.03	1.17	1.971	YES	YES	YES	NO
M-NSA	E-TCA	14.20	12.53	3	3	1.03	1.17	1.832	YES	YES	NO	NO
M-NSA	E-TCB	14.20	14.99	3	3	1.03	1.03	-1.402	YES	NO	NO	NO
M-NSA	M-NSA*	14.20	15.34	3	3	1.03	1.03	-1.356	YES	NO	NO	NO
M-NSA	M-NSA**	14.20	15.50	3	3	1.03	1.03	-0.629	NO	NO	NO	NO
E-NSA	E-NSB	14.94	14.05	3	3	1.03	1.03	1.056	NO	NO	NO	NO
E-NSA	M-TCA	14.94	12.43	3	3	1.03	1.17	2.788	YES	YES	YES	YES
E-NSA	E-TCA	14.94	12.53	3	3	1.03	1.17	2.649	YES	YES	YES	YES
E-NSA	E-TCB	14.94	14.99	3	3	1.03	1.03	-0.057	NO	NO	NO	NO
E-NSA	M-NSA*	14.94	15.34	3	3	1.03	1.03	-0.481	NO	NO	NO	NO
E-NSA	M-NSA**	14.94	15.50	3	3	1.03	1.03	-0.668	NO	NO	NO	NO
E-NSB	M-TCA	14.05	12.43	3	3	1.03	1.17	1.802	YES	YES	NO	NO
E-NSB	E-TCA	14.05	12.53	3	3	1.03	1.17	1.664	YES	YES	NO	NO
E-NSB	E-TCB	14.05	14.99	3	3	1.03	1.03	-1.113	NO	NO	NO	NO
E-NSB	M-NSA*	14.05	15.34	3	3	1.03	1.03	-1.537	YES	NO	NO	NO
E-NSB	M-NSA**	14.05	15.50	3	3	1.03	1.03	-1.723	YES	YES	YES	NO
M-TCA	E-TCA	12.43	12.53	3	3	1.17	1.03	-0.131	NO	NO	NO	NO
M-TCA	E-TCB	12.43	14.99	3	3	1.17	1.03	-2.841	YES	YES	YES	YES
M-TCA	M-NSA*	12.43	15.34	3	3	1.17	1.03	-3.237	YES	YES	YES	YES
M-TCA	M-NSA**	12.43	15.50	3	3	1.17	1.03	-3.411	YES	YES	YES	YES
E-TCA	E-TCB	12.53	14.99	3	3	1.17	1.03	-2.702	YES	YES	YES	YES
E-TCA	M-NSA*	12.53	15.34	3	3	1.17	1.03	-3.098	YES	YES	YES	YES
E-TCA	M-NSA**	12.53	15.50	3	3	1.17	1.03	-3.272	YES	YES	YES	YES
E-TCB	M-NSA*	14.99	15.34	3	3	1.03	1.03	-0.424	NO	NO	NO	NO
E-TCB	M-NSA**	14.99	15.50	3	3	1.03	1.03	-0.610	NO	NO	NO	NO
M-NSA*	M-NSA**	15.34	15.50	3	3	1.03	1.03	-0.187	NO	NO	NO	NO

* Cleaning method: Brush with air, BA.

** Cleaning method: Air, A.

Table 3.3 (continued)

Bar Surface-Grout 1	Bar Surface-Grout 2	Mean Bond Str.,kips 1	Mean Bond Str.,kips 2	No. of Tests 1	No. of Tests 2	Std. Dev. 1	Std. Dev. 2	z(calc.)	$z(\alpha/2=0.10)=1.282$ H0 Rejected	$z(\alpha/2=0.05)=1.645$ H0 Rejected	$z(\alpha/2=0.025)=1.960$ H0 Rejected	$z(\alpha/2=0.01)=2.326$ H0 Rejected
SMALL HOLE VERSUS LARGE HOLE												
M-NSA	M-NSA	15.08	14.20	3	3	1.83	1.03	0.723	NO	NO	NO	NO
E-MSA	E-MSA	13.11	14.94	2	3	1.83	1.03	-1.291	YES	NO	NO	NO
E-NSB	E-NSB	14.17	14.06	3	3	1.83	1.03	0.102	NO	NO	NO	NO
M-TCA	M-TCA	10.23	12.43	3	3	2.15	1.17	-1.556	YES	NO	NO	NO
E-TCA	E-TCA	11.74	12.53	3	3	2.15	1.17	-0.576	NO	NO	NO	NO
E-TCB	E-TCB	15.81	14.99	3	3	1.83	1.03	0.681	NO	NO	NO	NO

Table 3.4: Statistical Data for No. 8 Bars in Groups 8, 9 and 10. All bars epoxy-coated. Hole Cleaning Method: Vacuum, V; Brush with water, BW; Brush with air, BA; and Air, A

Grout/Hole Cl. Method	Norm. Bond Str., kips Gp. 8	Gp. 9	Gp. 10	Mean Bond Str., Xm, kips	SUM (Xi-Xm)^2	No. of Tests	Std. Deviation
NSA/V	25.367	24.107	24.965	24.813	0.828	3	0.643
NSA/BW	25.645	22.079	27.874	25.199	17.088	3	2.923
NSA/BA	24.058	20.437	25.146	23.214	12.155	3	2.465
NSA/A	22.317	23.315	26.209	23.947	8.172	3	2.021
TCB/V	24.975	27.439	22.287	24.900	13.282	3	2.577
TCB/BW	22.183	27.430	24.594	24.735	13.794	3	2.626
TCB/BA	26.582	24.880	23.270	24.911	5.488	3	1.656
TCB/A	24.336	25.305	24.885	24.842	0.472	3	0.486
CPA/V	26.912	25.170	25.045	25.709	2.179	3	1.044
CPA/BW	28.128	24.291	27.683	26.701	8.810	3	2.099
CPA/BA	28.653	26.686	29.348	28.229	3.813	3	1.381
CPA/A	28.076	27.488	26.921	27.495	0.668	3	0.578
				SUM=	86.748		
				Std. Dev.=	1.901		
TCA/V	24.584	22.282	23.410	23.425	2.649	3	1.151
TCA/BW	15.939	17.491	16.459	16.630	1.248	3	0.790
TCA/BA	16.289	11.155	16.389	14.611	17.921	3	2.993
TCA/A	20.462	16.003	13.811	16.759	22.947	3	3.389
				SUM=	44.792		
				Std. Dev.=	2.366		

Table 3.5: Hypothesis Testing using Student t-Test for No. 8 Bars in Groups 8, 9 and 10. All bars epoxy-coated.
Cleaning Method: Vacuum, V; Brush with water, BW; Brush with air, BA; and Air, A.
Null Hypothesis, H0: Mean bond strength of population 1 = Mean bond strength of population 2

Grout/Hole Cl. Method 1	2	Mean Bond Str.,kips 1	2	No. of Tests 1	2	Std. Dev. 1	2	t(calc.)	t ($\alpha/2$=0.10)=1.533 H0 Rejected	t ($\alpha/2$=0.05)=2.132 H0 Rejected	t ($\alpha/2$=0.025)=2.776 H0 Rejected	t ($\alpha/2$=0.01)=3.747 H0 Rejected
NSA/V	TCA/V	24.81	23.43	3	3	0.64	1.15	1.816	YES	NO	NO	NO
NSA/V	TCB/V	24.81	24.90	3	3	0.64	2.58	-0.059	NO	NO	NO	NO
NSA/V	CPA/V	24.81	25.71	3	3	0.64	1.04	-1.277	NO	NO	NO	NO
TCA/V	TCB/V	23.43	24.90	3	3	1.15	2.58	-0.901	NO	NO	NO	NO
TCA/V	CPA/V	23.43	25.71	3	3	1.15	1.04	-2.547	YES	YES	NO	NO
TCB/V	CPA/V	24.90	25.71	3	3	2.58	1.04	-0.543	NO	NO	NO	NO
NSA/BW	TCA/BW	25.20	16.63	3	3	2.92	0.79	4.907	YES	YES	YES	YES
NSA/BW	TCB/BW	25.20	24.74	3	3	2.92	2.62	0.203	NO	NO	NO	NO
NSA/BW	CPA/BW	25.20	26.70	3	3	2.92	2.10	-0.722	NO	NO	NO	NO
TCA/BW	TCB/BW	16.63	24.74	3	3	0.79	2.62	-5.115	YES	YES	YES	YES
TCA/BW	CPA/BW	16.63	26.70	3	3	0.79	2.10	-7.774	YES	YES	YES	YES
TCB/BW	CPA/BW	24.74	26.70	3	3	2.63	2.10	-1.009	NO	NO	NO	NO
NSA/BA	TCA/BA	23.21	14.61	3	3	2.47	2.99	3.841	YES	YES	YES	YES
NSA/BA	TCB/BA	23.21	24.91	3	3	2.47	1.66	-0.989	NO	NO	NO	NO
NSA/BA	CPA/BA	23.21	28.23	3	3	2.47	1.38	-3.073	YES	YES	YES	NO
TCA/BA	TCB/BA	14.61	24.91	3	3	2.99	1.66	-5.217	YES	YES	YES	YES
TCA/BA	CPA/BA	14.61	28.23	3	3	2.99	1.38	-7.164	YES	YES	YES	YES
TCB/BA	CPA/BA	24.91	28.23	3	3	1.66	1.38	-2.664	YES	YES	NO	NO
NSA/A	TCA/A	23.95	16.75	3	3	2.02	3.39	2.987	YES	YES	YES	NO
NSA/A	TCB/A	23.95	24.84	3	3	2.02	0.49	-0.742	NO	NO	NO	NO
NSA/A	CPA/A	23.95	27.50	3	3	2.02	0.58	-2.917	YES	YES	YES	NO
TCA/A	TCB/A	16.76	24.84	3	3	3.52	0.49	-4.065	YES	YES	YES	YES
TCA/A	CPA/A	16.76	27.50	3	3	3.52	0.58	-5.336	YES	YES	YES	YES
TCB/A	CPA/A	24.84	27.50	3	3	0.49	0.58	-6.045	YES	YES	YES	YES
NSA/V	NSA/BW	24.81	25.20	3	3	0.64	2.92	-0.527	NO	NO	NO	NO
NSA/V	NSA/BA	24.81	23.21	3	3	0.64	2.47	1.086	NO	NO	NO	NO
NSA/V	NSA/A	24.81	23.95	3	3	0.64	2.02	0.703	NO	NO	NO	NO
TCA/V	TCA/BW	23.43	16.63	3	3	1.15	0.79	8.442	YES	YES	YES	YES
TCA/V	TCA/BA	23.43	14.61	3	3	1.15	2.99	4.769	YES	YES	YES	YES

Table 3.5 (continued)

Grout/Hole Cl. Method 1	Grout/Hole Cl. Method 2	Mean Bond Str.,kips 1	Mean Bond Str.,kips 2	No. of Tests 1	No. of Tests 2	Std. Dev. 1	Std. Dev. 2	t(calc.)	t ($\alpha/2$=0.10)=1.533 H0 Rejected	t ($\alpha/2$=0.05)=2.132 H0 Rejected	t ($\alpha/2$=0.025)=2.776 H0 Rejected	t ($\alpha/2$=0.01)=3.747 H0 Rejected
TCA/V	TCA/A	23.43	16.76	3	3	1.15	3.39	3.251	YES	YES	YES	NO
TCB/V	TCB/BW	24.90	24.74	3	3	2.58	2.58	-1.335	NO	NO	NO	NO
TCB/V	TCB/BA	24.90	24.91	3	3	2.58	1.66	-0.006	NO	NO	NO	NO
TCB/V	TCB/A	24.90	24.84	3	3	2.58	0.49	0.040	NO	NO	NO	NO
CPA/V	CPA/BW	25.71	26.70	3	3	1.04	2.10	-0.732	NO	NO	NO	NO
CPA/V	CPA/BA	25.71	28.23	3	3	1.04	1.38	-2.526	YES	YES	NO	NO
CPA/V	CPA/A	25.71	27.50	3	3	1.04	0.59	-2.589	YES	YES	NO	NO
NSA/BW	NSA/BA	25.20	23.21	3	3	2.92	2.47	1.137	NO	NO	NO	NO
NSA/BW	NSA/A	25.20	23.95	3	3	2.92	2.02	0.863	NO	NO	NO	NO
NSA/BA	NSA/A	23.21	23.95	3	3	2.47	2.02	-0.402	NO	NO	NO	NO
TCA/BW	TCA/BA	16.63	14.61	3	3	0.79	2.99	1.131	NO	NO	NO	NO
TCA/BW	TCA/A	16.63	16.76	3	3	0.79	3.39	0.072	NO	NO	NO	NO
TCA/BA	TCA/A	14.61	16.76	3	3	2.99	3.39	-0.709	NO	NO	NO	NO
TCB/BW	TCB/BA	24.74	24.91	3	3	2.63	1.66	1.576	YES	NO	NO	NO
TCB/BW	TCB/A	24.74	24.84	3	3	2.63	0.49	1.878	YES	NO	NO	NO
TCB/BA	TCB/A	24.91	24.84	3	3	1.66	0.49	0.070	NO	NO	NO	NO
CPA/BW	CPA/BA	26.70	28.23	3	3	2.10	1.38	-1.055	NO	NO	NO	NO
CPA/BW	CPA/A	26.70	27.50	3	3	2.10	0.59	-0.628	NO	NO	NO	NO
CPA/BA	CPA/A	28.23	27.50	3	3	1.38	0.59	0.856	NO	NO	NO	NO

Table 3.6: Hypothesis Testing using "z-test" for No. 8 Bars in Groups 8, 9 and 10. All bars epoxy-coated.
Cleaning Method : Vacuum, V; Brush with water, BW; Brush with air, BA; and Air, A.
Null Hypothesis, H0: Mean bond strength of population 1 = Mean bond strength of population 2

Grout/Hole Cl. Method 1	2	Mean Bond Str.,kips 1	2	No. of Tests 1	2	Std. Dev. 1	2	z(calc.)	$z(\alpha/2=0.10)=1.282$ H0 Rejected	$z(\alpha/2=0.05)=1.645$ H0 Rejected	$z(\alpha/2=0.025)=1.960$ H0 Rejected	$z(\alpha/2=0.01)=2.326$ H0 Rejected
NSA/V	TCA/V	24.81	23.40	3	3	1.90	2.37	0.787	NO	NO	NO	NO
NSA/V	TCB/V	24.81	24.90	3	3	1.90	1.90	-0.060	NO	NO	NO	NO
NSA/V	CPA/V	24.81	25.70	3	3	1.90	1.90	-0.580	NO	NO	NO	NO
TCA/V	TCB/V	23.43	24.90	3	3	2.37	1.90	-0.840	NO	NO	NO	NO
TCA/V	CPA/V	23.43	25.70	3	3	2.37	1.90	-1.300	YES	NO	NO	NO
TCB/V	CPA/V	24.90	25.70	3	3	2.37	1.90	-0.460	NO	NO	NO	NO
NSA/BW	TCA/BW	25.20	16.60	3	3	1.90	2.37	4.890	YES	YES	YES	YES
NSA/BW	TCB/BW	25.20	24.70	3	3	1.90	1.90	0.296	NO	NO	NO	NO
NSA/BW	CPA/BW	25.20	26.70	3	3	1.90	1.90	-0.970	NO	NO	NO	NO
TCA/BW	TCB/BW	16.63	24.70	3	3	2.37	1.90	-4.630	YES	YES	YES	YES
TCA/BW	CPA/BW	16.63	26.70	3	3	2.37	1.90	-5.750	YES	YES	YES	YES
TCB/BW	CPA/BW	24.74	26.70	3	3	1.90	1.90	-1.260	NO	NO	NO	NO
NSA/BA	TCA/BA	23.21	14.60	3	3	1.90	2.37	4.907	YES	YES	YES	YES
NSA/BA	TCB/BA	23.21	24.90	3	3	1.90	1.90	-1.100	NO	NO	NO	NO
NSA/BA	CPA/BA	23.21	28.20	3	3	1.90	1.90	-3.230	YES	YES	YES	YES
TCA/BA	TCB/BA	14.61	24.90	3	3	2.37	1.90	-5.880	YES	YES	YES	YES
TCA/BA	CPA/BA	14.61	28.20	3	3	2.37	1.90	-7.770	YES	YES	YES	YES
TCB/BA	CPA/BA	24.91	28.20	3	3	1.90	1.90	-2.140	YES	YES	YES	NO
NSA/A	TCA/A	23.95	17.00	3	3	1.90	2.37	3.994	YES	YES	YES	YES
NSA/A	TCB/A	23.95	24.80	3	3	1.90	1.90	-0.570	NO	NO	NO	NO
NSA/A	CPA/A	23.95	27.50	3	3	1.90	1.90	-2.280	YES	YES	YES	NO
TCA/A	TCB/A	16.50	24.80	3	3	2.37	1.90	-5.370	YES	YES	YES	YES
TCA/A	CPA/A	16.50	27.50	3	3	2.37	1.90	-6.270	YES	YES	YES	YES
TCB/A	CPA/A	24.84	27.50	3	3	1.90	1.90	-1.510	YES	NO	NO	NO
NSA/V	NSA/BW	24.81	25.70	3	3	1.90	1.90	-0.590	NO	NO	NO	NO
NSA/V	NSA/BA	24.81	23.20	3	3	1.90	1.90	1.031	NO	NO	NO	NO
NSA/V	NSA/A	24.81	24.00	3	3	1.90	1.90	0.554	NO	NO	NO	NO
TCA/V	TCA/BW	23.43	16.60	3	3	2.37	2.37	3.520	YES	YES	YES	YES
TCA/V	TCA/BA	23.43	14.60	3	3	2.37	2.37	4.565	YES	YES	YES	YES

Table 3.6 (continued)

Grout/Hole	Cl. Method	Mean Bond Str.,kips		No. of Tests		Std. Dev.		t(calc.)	t (α/2=0.10)=1.533	t (α/2=0.05)=2.132	t (α/2=0.025)=2.776	t (α/2=0.01)=3.747
1	2	1	2	1	2	1	2		H0 Rejected	H0 Rejected	H0 Rejected	H0 Rejected
TCA/V	TCA/A	23.43	16.50	3	3	2.37	2.37	3.597	YES	YES	YES	NO
TCB/V	TCB/BW	24.90	27.70	3	3	1.90	1.90	-1.830	NO	YES	NO	NO
TCB/V	TCB/BA	24.90	24.90	3	3	1.90	1.90	-0.010	NO	NO	NO	NO
TCB/V	TCB/A	24.90	24.80	3	3	1.90	1.90	0.039	NO	NO	NO	NO
CPA/V	CPA/BW	25.71	26.70	3	3	1.90	1.90	-0.640	NO	NO	NO	NO
CPA/V	CPA/BA	25.71	28.20	3	3	1.90	1.90	-1.620	YES	NO	NO	NO
CPA/V	CPA/A	25.71	27.50	3	3	1.90	1.90	-1.150	NO	NO	NO	NO
NSA/BW	NSA/BA	25.72	23.20	3	3	1.90	1.90	1.617	YES	NO	NO	NO
NSA/BW	NSA/A	25.72	24.00	3	3	1.90	1.90	1.140	NO	NO	NO	NO
NSA/BA	NSA/A	23.21	24.00	3	3	1.90	1.90	-0.480	NO	NO	NO	NO
TCA/BW	TCA/BA	16.63	14.60	3	3	2.37	2.37	1.046	NO	NO	NO	NO
TCA/BW	TCA/A	16.63	16.50	3	3	2.37	2.37	0.078	NO	NO	NO	NO
TCA/BA	TCA/A	14.61	16.50	3	3	2.37	2.37	-0.980	NO	NO	NO	NO
TCB/BW	TCB/BA	27.74	24.90	3	3	1.90	1.90	1.823	YES	YES	NO	NO
TCB/BW	TCB/A	27.74	24.80	3	3	1.90	1.90	1.868	YES	YES	NO	NO
TCB/BA	TCB/A	24.91	24.80	3	3	1.90	1.90	0.045	NO	NO	NO	NO
CPA/BW	CPA/BA	26.70	28.20	3	3	1.90	1.90	-0.990	NO	NO	NO	NO
CPA/BW	CPA/A	26.70	27.50	3	3	1.90	1.90	-0.510	NO	NO	NO	NO
CPA/BA	CPA/A	28.23	27.50	3	3	1.90	1.90	0.477	NO	NO	NO	NO

Table 3.7: Statistical Data and Hypothesis Testing for No. 5 Bars in Group 11 Comparing 1) the Effect of Number of Capsules and Number of Revolutions for Anchoring Bars with CPA Grout and 2) Vacuum, V, and Brush with air, BA, Hole Cleaning Methods for Bars Anchored with TCA Grout

Grout-ID	Norm. Bond Str.,kips 1	2	3	Mean Bond Str., Xm,kips	SUM (Xi-Xm)^2	No. of Tests	Std Deviation
CPA-1S*	15.26	13.30	11.10	13.22	8.68	3	2.08
CPA-2S	15.00	13.77	13.91	14.23	0.89	3	0.67
CPA-1E	16.82	16.35	13.03	15.40	8.51	3	2.06
CPA-2E	14.50	14.32	14.12	14.31	0.07	3	0.19
				SUM=	18.15		
				Std. Dev.=	1.51		
TCA/V	9.64	12.00	11.60	11.08	3.20	3	1.26
TCA/BA	6.71	12.80	10.49	10.00	18.92	3	3.08
				SUM=	22.12		
				Std. Dev.=	2.35		

* 1S = one capsule, standard number of revolutions
2S = two capsules, standard number of revolutions
1E = one capsule, extra revolutions
2E = two capsules, extra revolutions

Table 3.8: Hypothesis Testing unsig Student t-test and "z-test" for No. 5 Bars in Group 11 Comparing 1) the Effect of Number of Capsules and Number of Revolutions for Anchoring Bars with CPA Grout and 2) Vacuum, V, and Brush with air, BA, Hole Cleaning Methods for Bars Anchored with TCA Grout

Grout - ID		Mean Bond Str.,kips		No. of Tests		Std. Dev.		t(calc.)	t ($\alpha/2$=0.10)=1.282	t ($\alpha/2$=0.05)=1.645	t ($\alpha/2$=0.025)=1.960	t ($\alpha/2$=0.01)=2.326
1	2	1	2	1	2	1	2		H0 Rejected	H0 Rejected	H0 Rejected	H0 Rejected
CPA-1S*	CPA-2S	13.22	14.22	3	3	2.08	0.67	-0.792	NO	NO	NO	NO
CPA-1S	CPA-1E	13.22	15.40	3	3	2.08	2.06	-1.288	NO	NO	NO	NO
CPA-1S	CPA-2E	13.22	11.31	3	3	2.08	0.19	-0.902	NO	NO	NO	NO
CPA-2S	CPA-1E	14.22	15.40	3	3	0.67	2.06	-0.943	NO	NO	NO	NO
CPA-2S	CPA-2E	14.22	14.31	3	3	0.67	0.19	-0.225	NO	NO	NO	NO
CPA-1S	CPA-2E	15.40	14.31	3	3	2.08	0.19	0.912	NO	NO	NO	NO
TCA/V	TCA/BA	11.08	10.00	3	3	1.26	3.08	0.563	NO	NO	NO	NO

Grout - ID		Mean Bond Str.,kips		No. of Tests		Std. Dev.		z(calc.)	z ($\alpha/2$=0.10)=1.282	z ($\alpha/2$=0.05)=1.645	z ($\alpha/2$=0.025)=1.960	z ($\alpha/2$=0.01)=2.326
1	2	1	2	1	2	1	2		H0 Rejected	H0 Rejected	H0 Rejected	H0 Rejected
CPA-1S	CPA-2S	13.22	14.22	3	3	1.51	1.51	-0.813	NO	NO	NO	NO
CPA-1S	CPA-1E	13.22	15.40	3	3	1.51	1.51	-1.772	YES	YES	NO	NO
CPA-1S	CPA-2E	13.22	14.31	3	3	1.51	1.51	-0.886	NO	NO	NO	NO
CPA-2S	CPA-1E	14.22	15.40	3	3	1.51	1.51	-0.959	NO	NO	NO	NO
CPA-2S	CPA-2E	14.22	14.31	3	3	1.51	1.51	-0.073	NO	NO	NO	NO
CPA-1S	CPA-2E	15.40	14.31	3	3	1.51	1.51	0.886	NO	NO	NO	NO
TCA/V	TCA/BA	11.08	10.00	3	3	2.35	2.35	0.563	NO	NO	NO	NO

* 1S = one capsule, standard number of revolutions
2S = two capsules, standard number of revolutions
1E = one capsule, extra revolutions
2E = two capsules, extrta revolutions

Table 5.1: Field Tests

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
			Field Test 1				
18	5VC-E-9-7/8BA	NSA	3	5600#	26.57	25.11	Pullout
18	5VC-E-9-7/8BA	NSA	3	5600#	27.22	25.71	Pullout
18	5VC-E-9-7/8BA	NSA	3	5600#	28.51	26.94	Pullout
Avg						25.92	
18	5VC-E-9-7/8BA	TCB	3	5600#	29.15	27.55	IGC
18	5VC-E-9-7/8BA	TCB	3	5600#	27.22	25.72	IGC
18	5VC-E-9-7/8BA	TCB	3	5600#	27.86	26.33	IGC
Avg						26.53	
18	5VC-E-9-7/8BA	TCA	3	5600#	24.00	22.67	IGC
18	5VC-E-9-7/8BA	TCA	3	5600#	21.42	20.24	IGC
18	5VC-E-9-7/8BA	TCA	3	5600#	18.84	17.81	IGC
Avg						20.24	
# Estimate							
			Field Test 2				
19	5VC-E-6-7/8BA	NSA	2-15/16	4270	22.71	24.57	Pullout
19	5VC-E-9-7/8BA	NSA	2-13/16	4270	27.86	30.15	Pullout
19	5VC-E-12-7/8BA	NSA	2-7/8	4270	28.51	30.85	Pullout
19	5VC-E-6-7/8BA	TCB	2-11/16	4270	17.55	18.99	Pullout
19	5VC-E-9-7/8BA	TCB	2-11/16	4270	24	25.97	Pullout
19	5VC-E-12-7/8BA	TCB	3	4270	26.57	28.76	Pullout
19	5VC-E-6-7/8BA	CPA	3-1/16	4270	11.75	12.72	Pullout
19	5VC-E-9-7/8BA	CPA	3	4270	7.89	8.53	Pullout
19	5VC-E-12-7/8BA	CPA	2-3/4	4270	7.89	8.53	Pullout
19	5VC-E-6-7/8BA	TCA	2-15/16	4270	11.11	12.02	IGC
19	5VC-E-9-7/8BA	TCA	2-15/16	4270	18.84	20.39	IGC
19	5VC-E-12-7/8BA	TCA	2-15/16	4270	18.84	20.39	IGC
			Field Test 3				
20	5VC-E-6-7/8BA	NSA	2-3/4	5490	20.77	19.82	Pullout
20	5VC-E-9-7/8BA	NSA	3	5490	26.52	25.36	S
20	5VC-E-12-7/8BA	NSA	2-13/16	5490	28.51	27.21	Pullout
20	5VC-E-6-7/8BA	TCB	2-7/8	5490	20.12	19.21	S
20	5VC-E-9-7/8BA	TCB	2-7/8	5490	25.28	24.13	S
20	5VC-E-12-7/8BA	TCB	3	5490	27.86	26.59	Pullout
20	5VC-E-6-7/8BA	CPA	3-3/16	5490	9.17	8.75	Pullout
20	5VC-E-9-7/8BA	CPA	2-3/4	5490	7.24	6.91	Pullout

Table 5.1: Field Tests, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
20	5VC-E-12-7/8BA	TCB	3	5490	27.86	26.59	Pullout
20	5VC-E-6-7/8BA	CPA	3-3/16	5490	9.17	8.75	Pullout
20	5VC-E-9-7/8BA	CPA	2-3/4	5490	7.24	6.91	Pullout
20	5VC-E-12-7/8BA	CPA	3	5490	5.95	5.68	Pullout
20	5VC-E-6-7/8BA	TCA	2-3/4	5490	14.97	14.29	IGC
20	5VC-E-9-7/8BA	TCA	3-1/8	5490	12.4	11.83	IGC
20	5VC-E-12-7/8BA	TCA	3-3/16	5490	20.13	19.21	IGC
			Field Test 4				
23	5VC-E-6-7/8BA	NSA	2-7/8	2700	9.82	13.36	S
23	5VC-E-6-7/8BA	CPA	3-3/16	2700	14.33	19.50	Pullout
23	5VC-E-6-7/8BA	TCA	3	2700	17.55	23.88	IGC

* Specimen Label: #ab-c-def

# = Bar Size, No. 5 or No. 8
a = Bar Orientation, H - horizontal or V - vertical
b = Bar Pattern, C or S
c = Bar surface, M - mill scale (uncoated), E - epoxy-coated
d = Embedment length, in.
e = Hole diameter, in.
f = Cleaning method, V - vacuum drilled, A - air, BA - brush with air, BW - brush with water

** Anchorage Method:

CIP = Cast-in-place;
CPA = Capsule A;
CPB = Capsule B;
TCA = Two-component grout A;
TCB = Two-compontent grout B;
NSA = Nonshrink grout A;
NSB = Nonshrink grout B;

*** Mod. bond strength = (Bond strength) $(5000/f'_c)^{.5}$

**** Failure Mode: S = Splitting; T = Tensile; IGC = interface between grout and concrete; Cone; Pullout

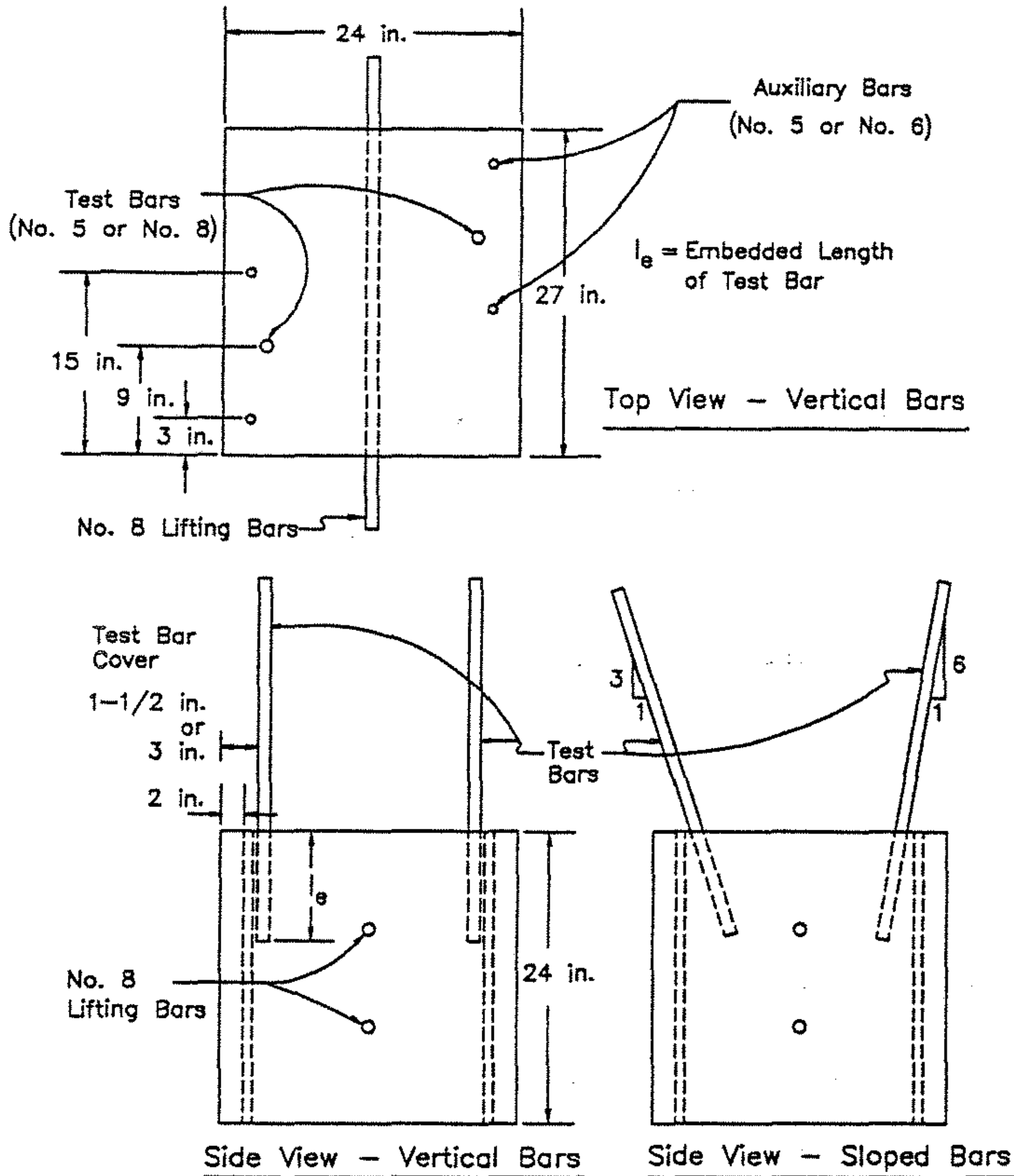

Fig. 2.1a Test Specimen with Vertical or Sloped Bars as Cast

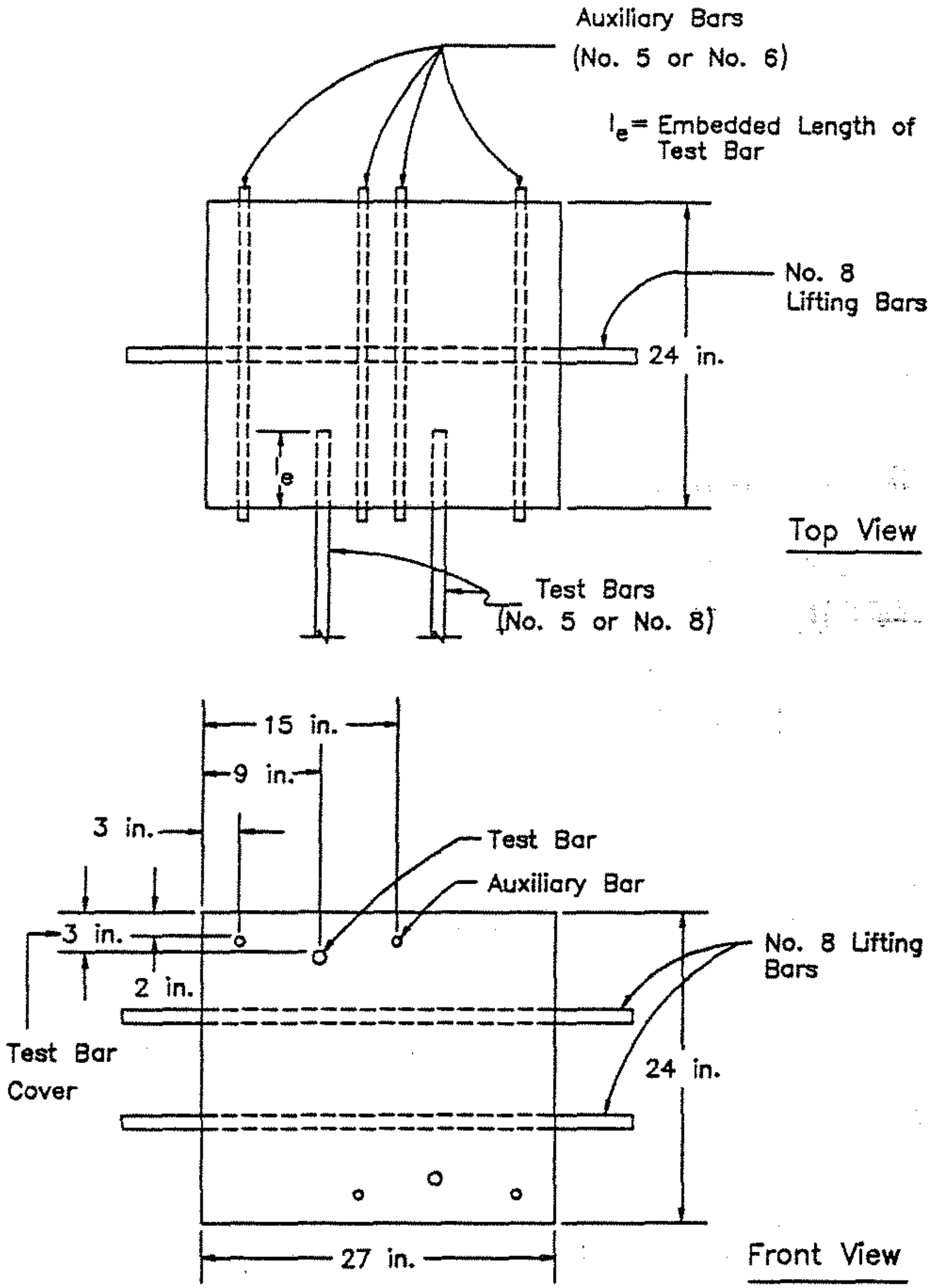

Fig. 2.1b Test Specimen with Horizontal Bars as Cast

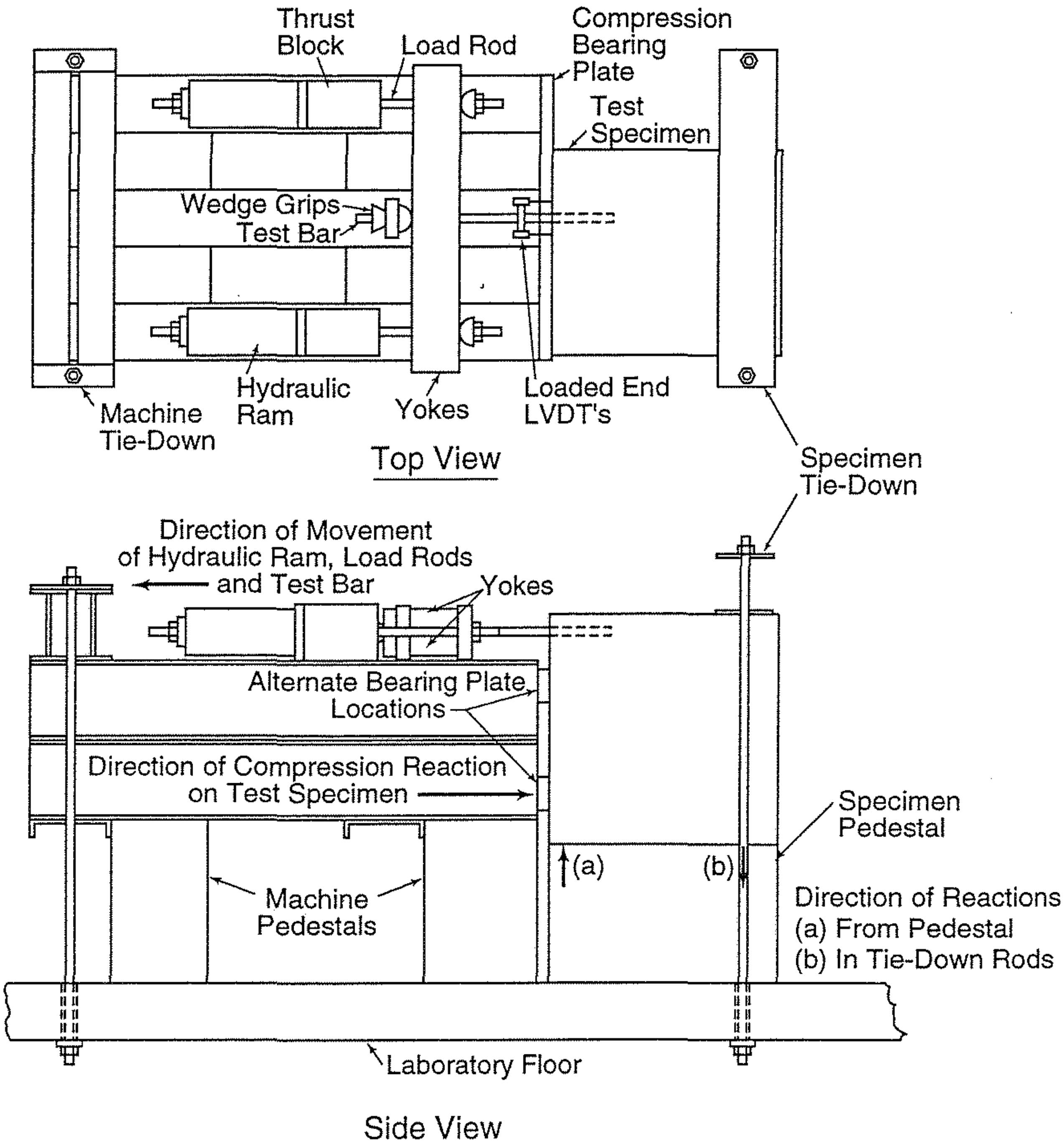

Fig. 2.2 Schematic of Test Setup

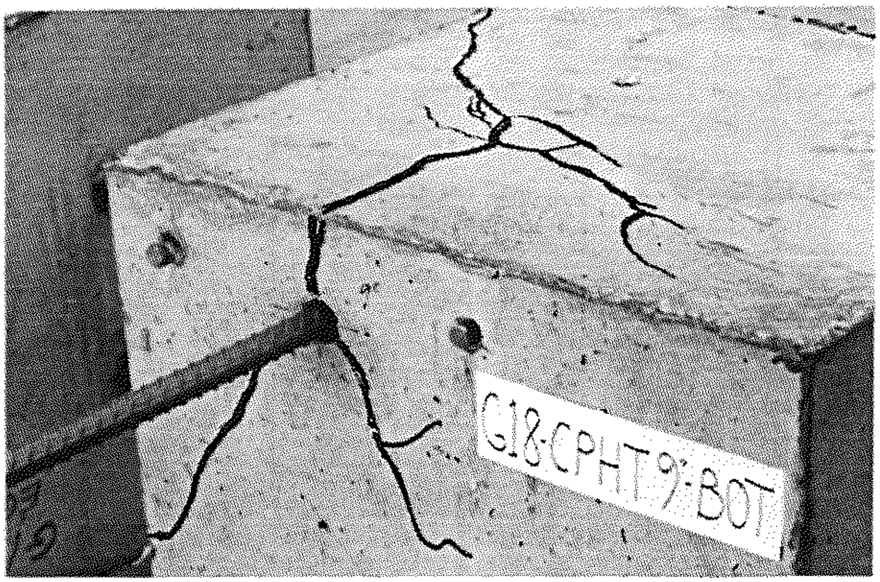

Fig. 2.3 Test Specimen Exhibiting a Splitting (S) Failure (Group 18, Specimen 8HC-B-E-9-1.25BA CPA)

Fig. 2.4 Test Specimen Exhibiting a Splitting (S) Failure (Group 18, Specimen 8HC-B-3-12-1.25BA NSA)

Fig. 2.5 Test Specimen Exhibiting a Cone Failure and a Failure at the Interface between Grout and Concrete (IGC) (Group 4, Specimen 5VC-E-6-1.5BW TCA)

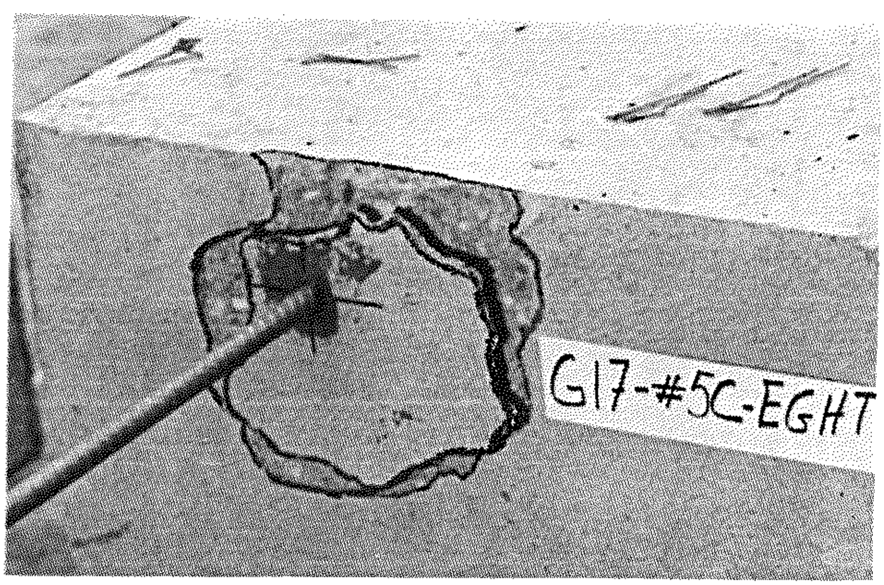

Fig. 2.6 Test Specimen Exhibiting a Cone Failure and a Failure at the Interface between Grout and Concrete (IGC) (Group 17, Specimen 5VC-E-6-7/8BA TCA)

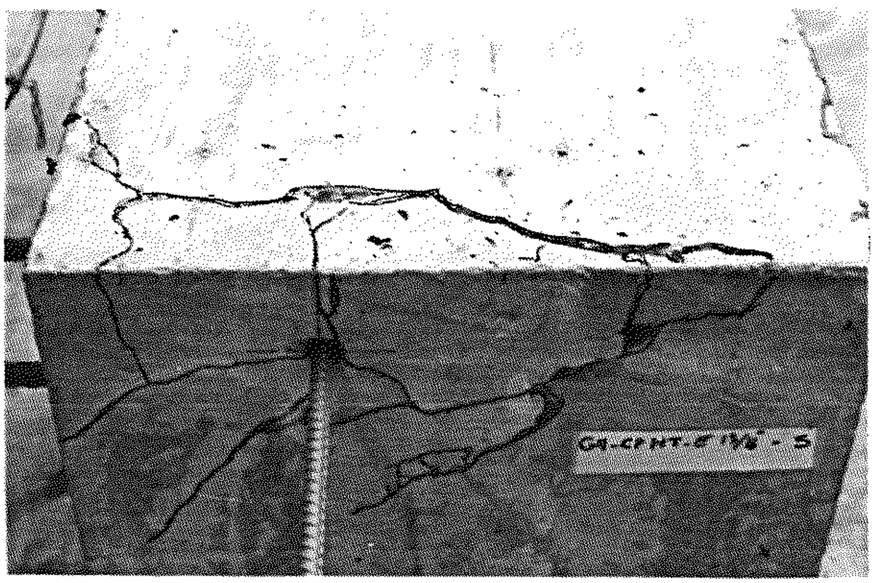

Fig. 2.7 Test Specimen Exhibiting a Combined Splitting (S) and Tensile (T) Failure (Group 4, Specimen 5 VC-E-6-13/16 BW CPA)

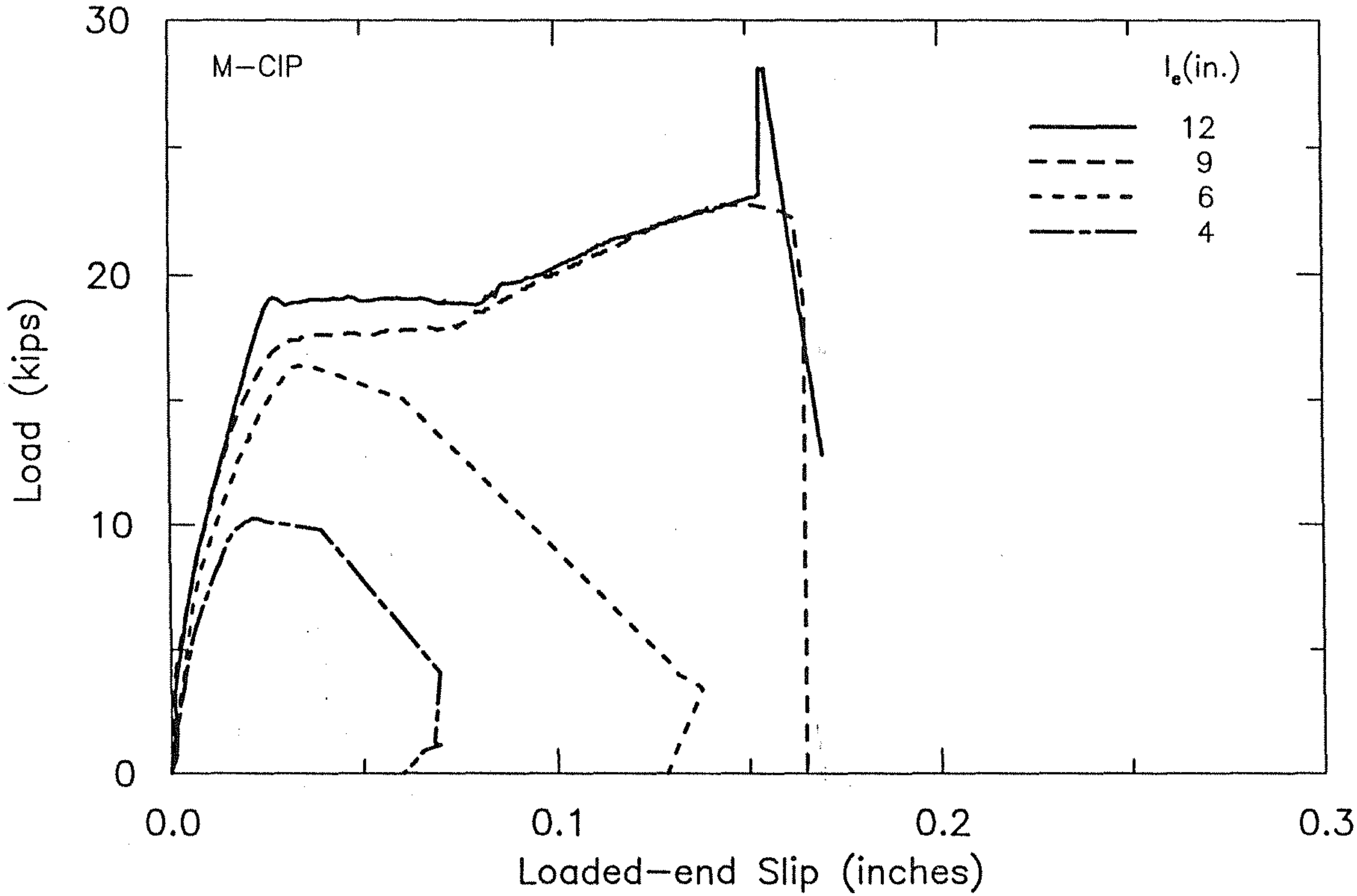

Fig. 2.8 Load-Slip Curves for Vertical Cast-in-place Uncoated No. 5 Bars with ℓ_e = 4, 6, 9, 12 in. (Group 17)

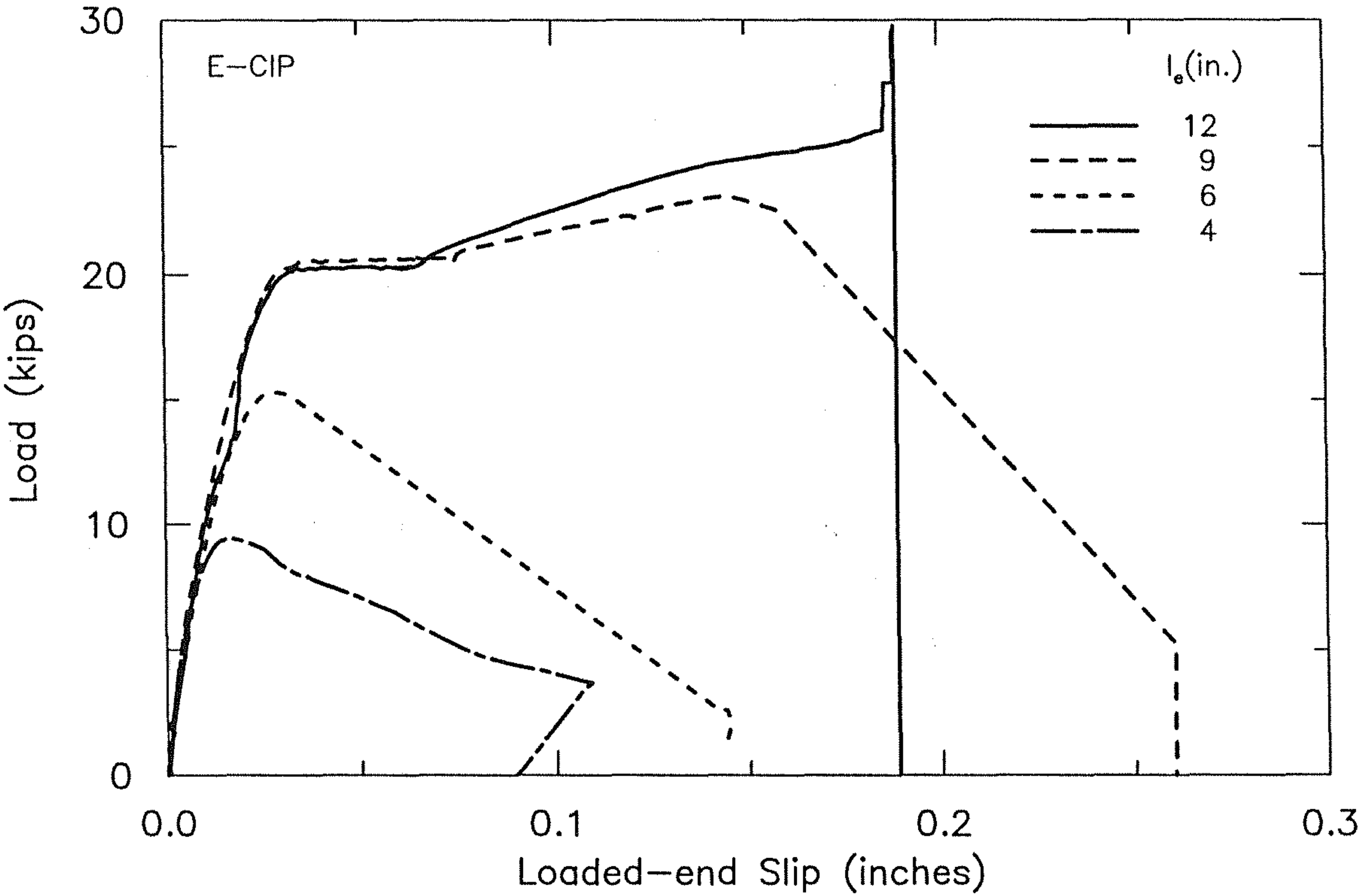

Fig. 2.9 Load-Slip Curves for Vertical Cast-in-place Epoxy-coated No. 5 Bars with ℓ_e = 4, 6, 9, 12 in. (Group 17)

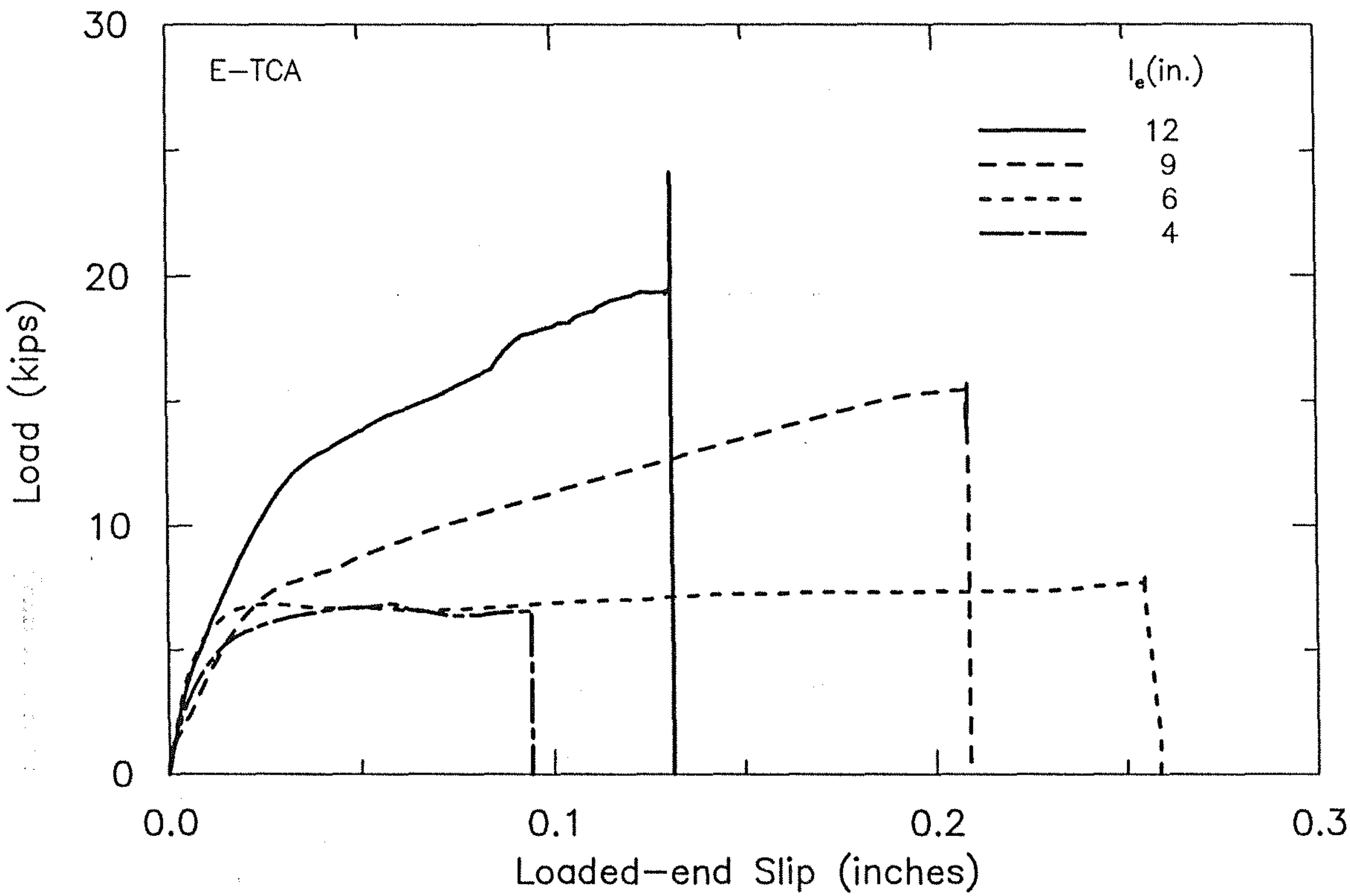

Fig. 2.10 Load-Slip Curves for Vertical TCA Grouted Epoxy-coated No. 5 Bars with ℓ_e = 4, 6, 9, 12 in. (Group 17)

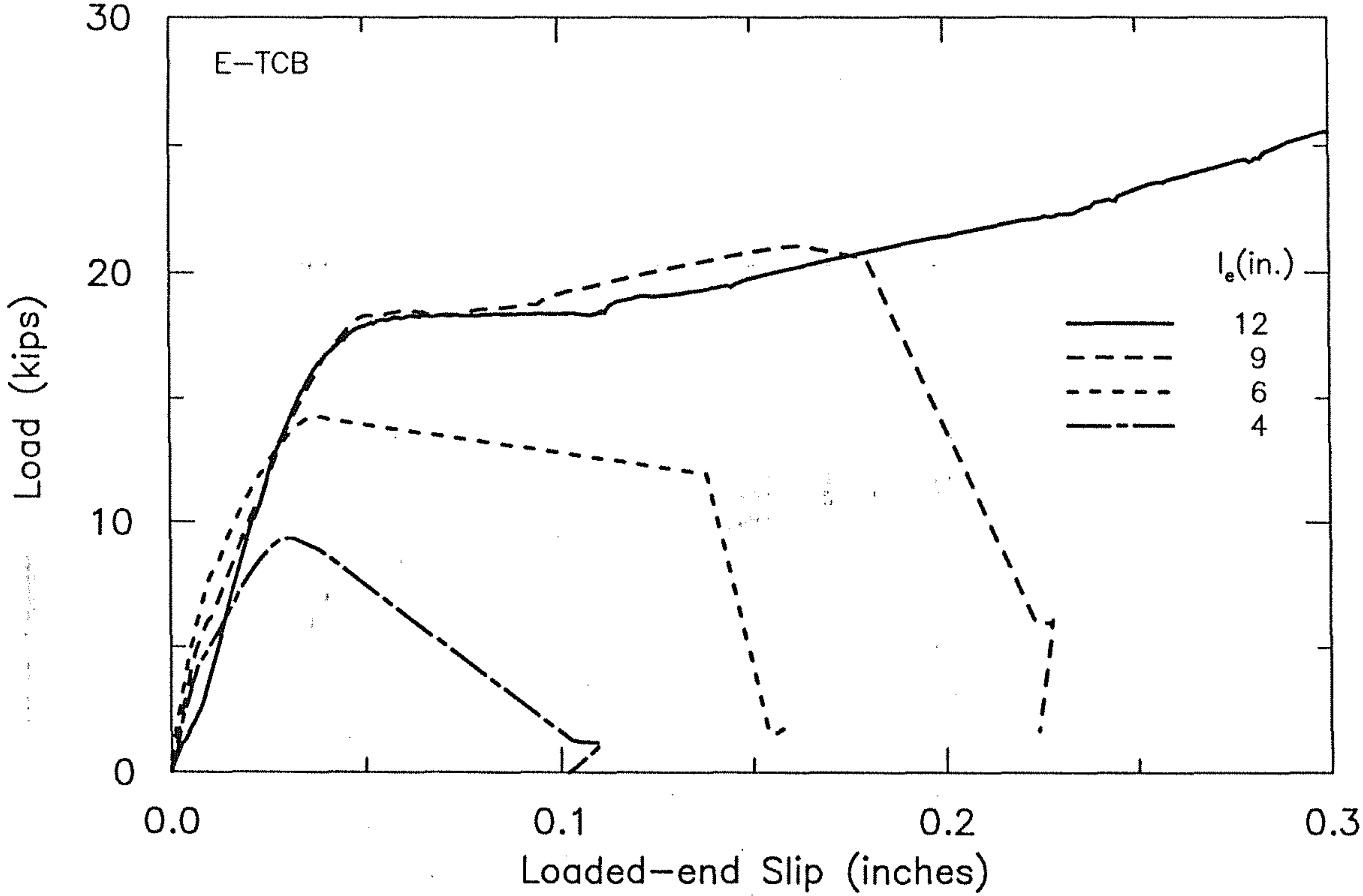

Fig. 2.11 Load-Slip Curves for Vertical TCB Grouted Epoxy-coated No. 5 Bars with ℓ_e = 4, 6, 9, 12 in. (Group 17)

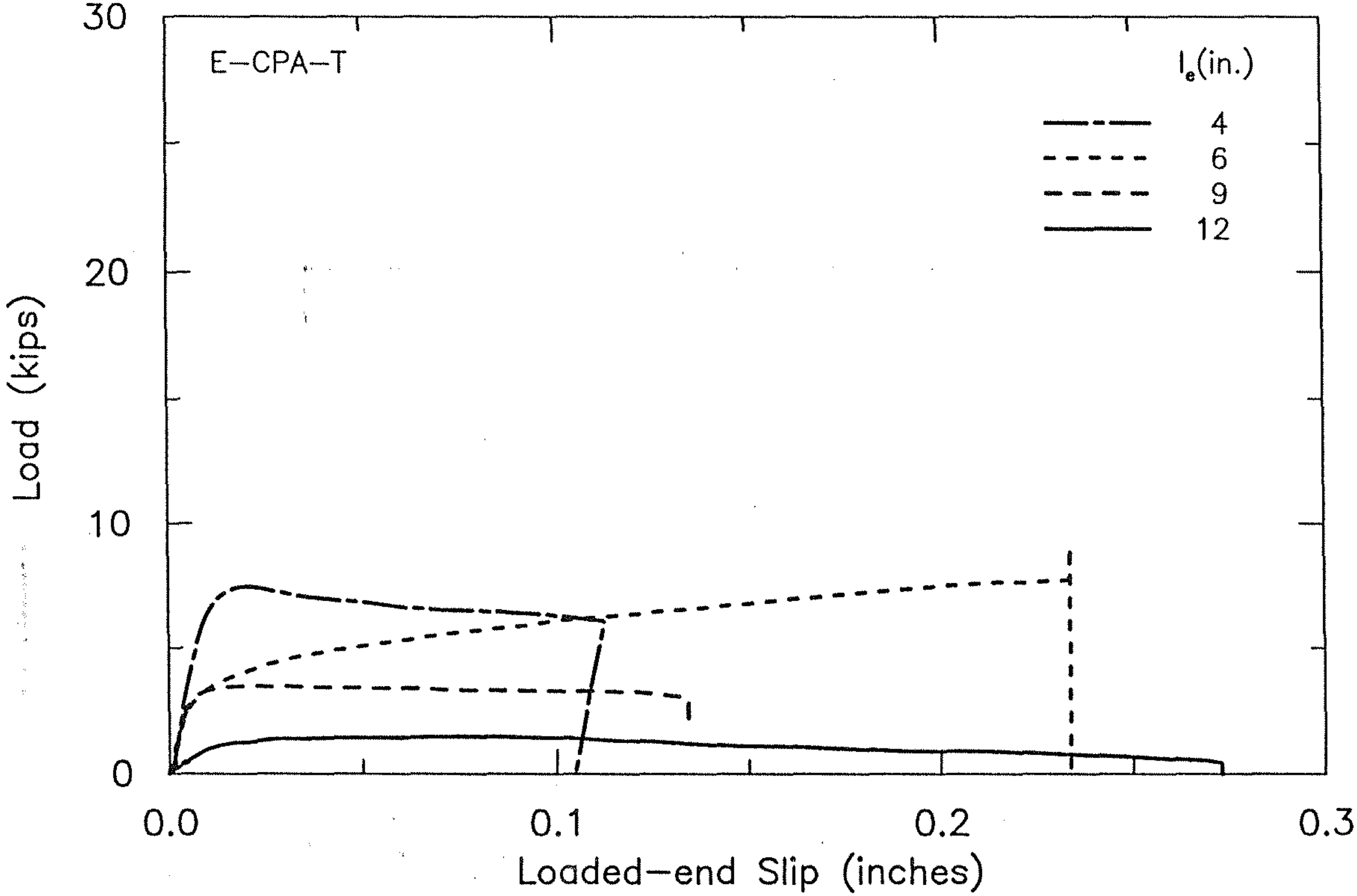

Fig. 2.12 Load-Slip Curves for Horizontal Top-cast CPA Grouted Epoxy-coated No. 5 Bars with ℓ_e = 4, 6, 9, 12 in. (Group 21). Note: Bond strength decreases with increasing embedment length.

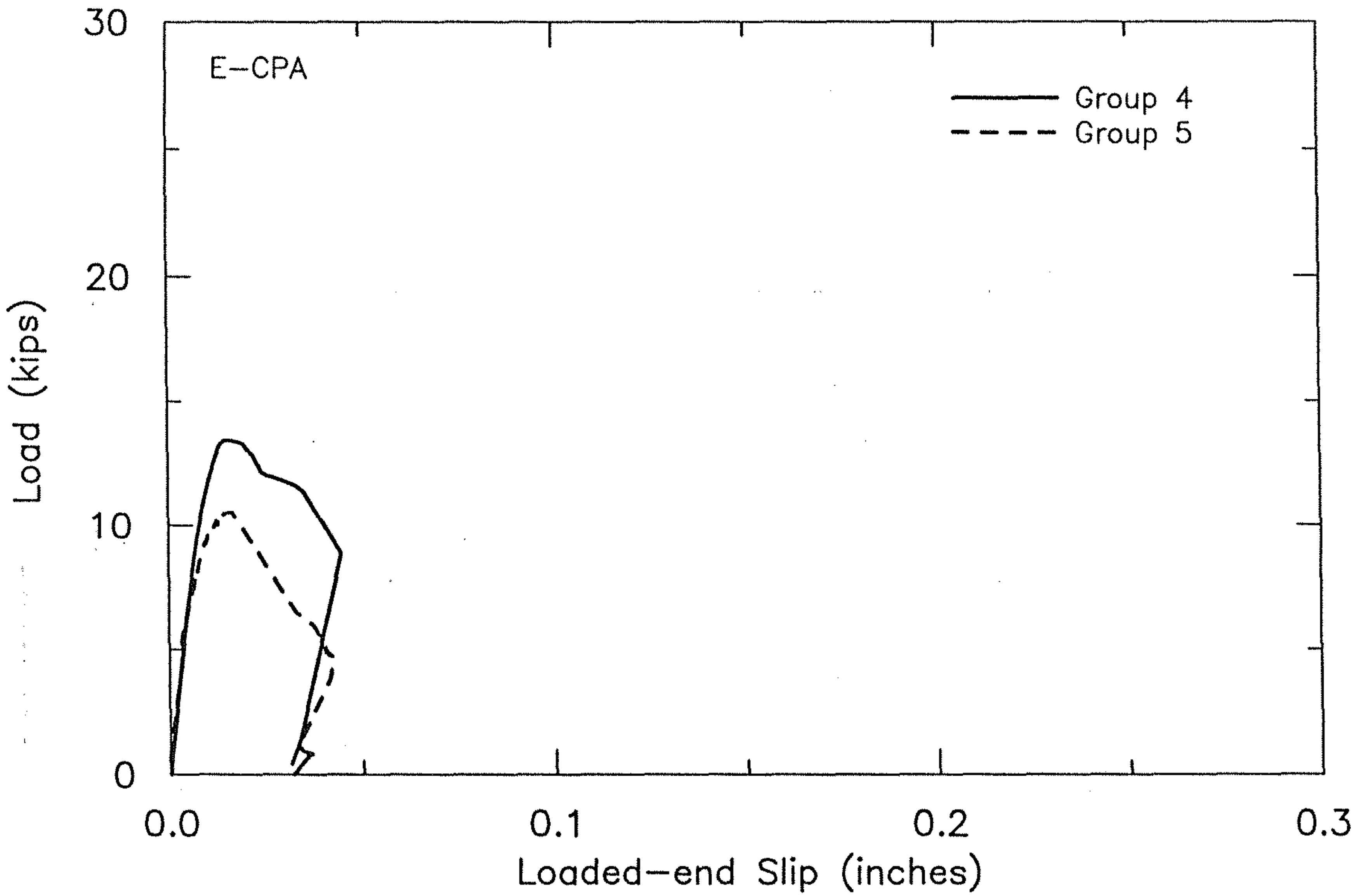

Fig. 2.13 Load-Slip Curves for Vertical CPA Grouted Epoxy-coated No. 5 Bars with ℓ_e = 6 in. (Groups 4 and 5)

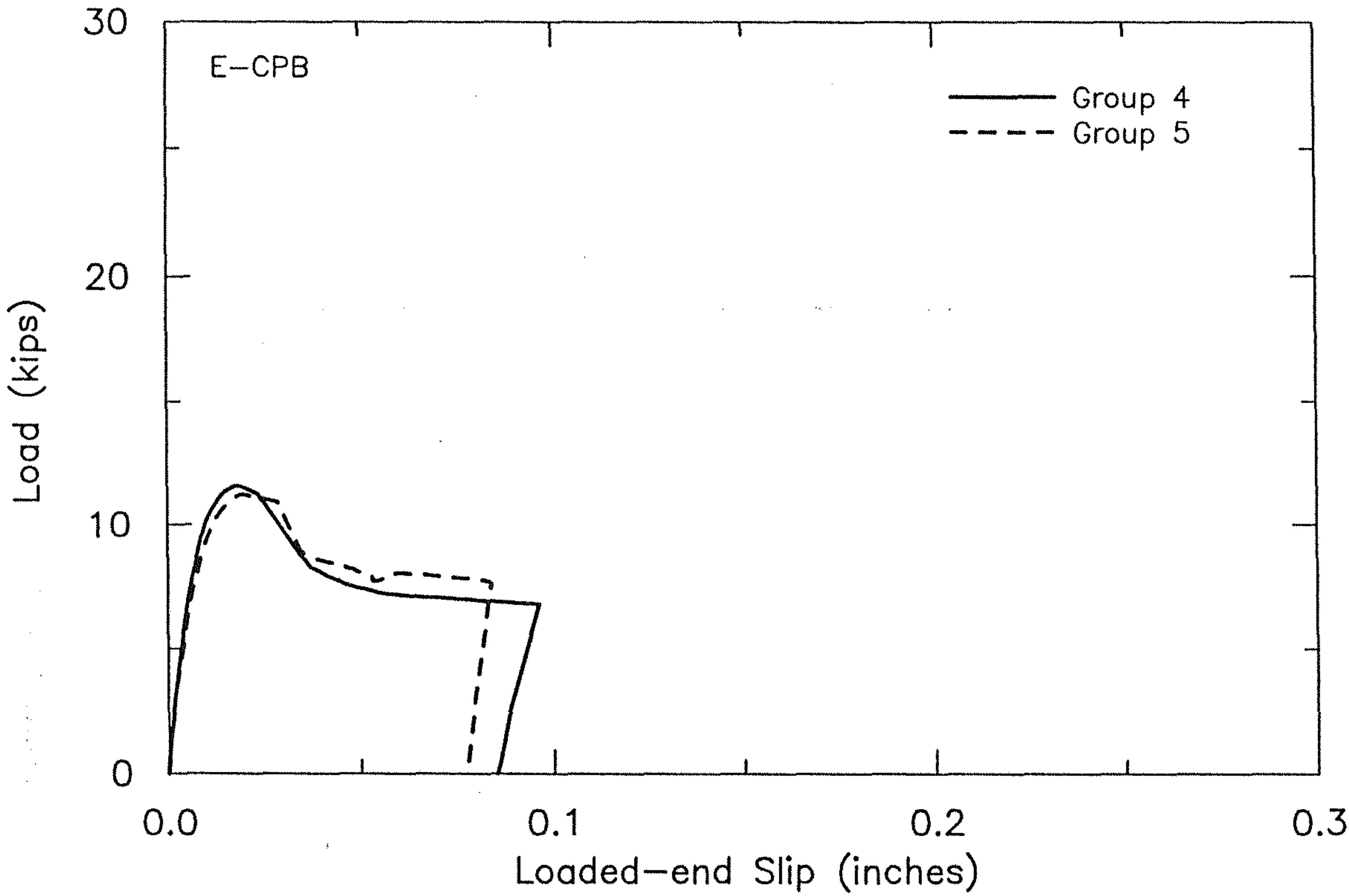

Fig. 2.14 Load-Slip Curves for Vertical CPB Grouted Epoxy-coated No. 5 Bars with $\ell_e = 6$ in. (Groups 4 and 5)

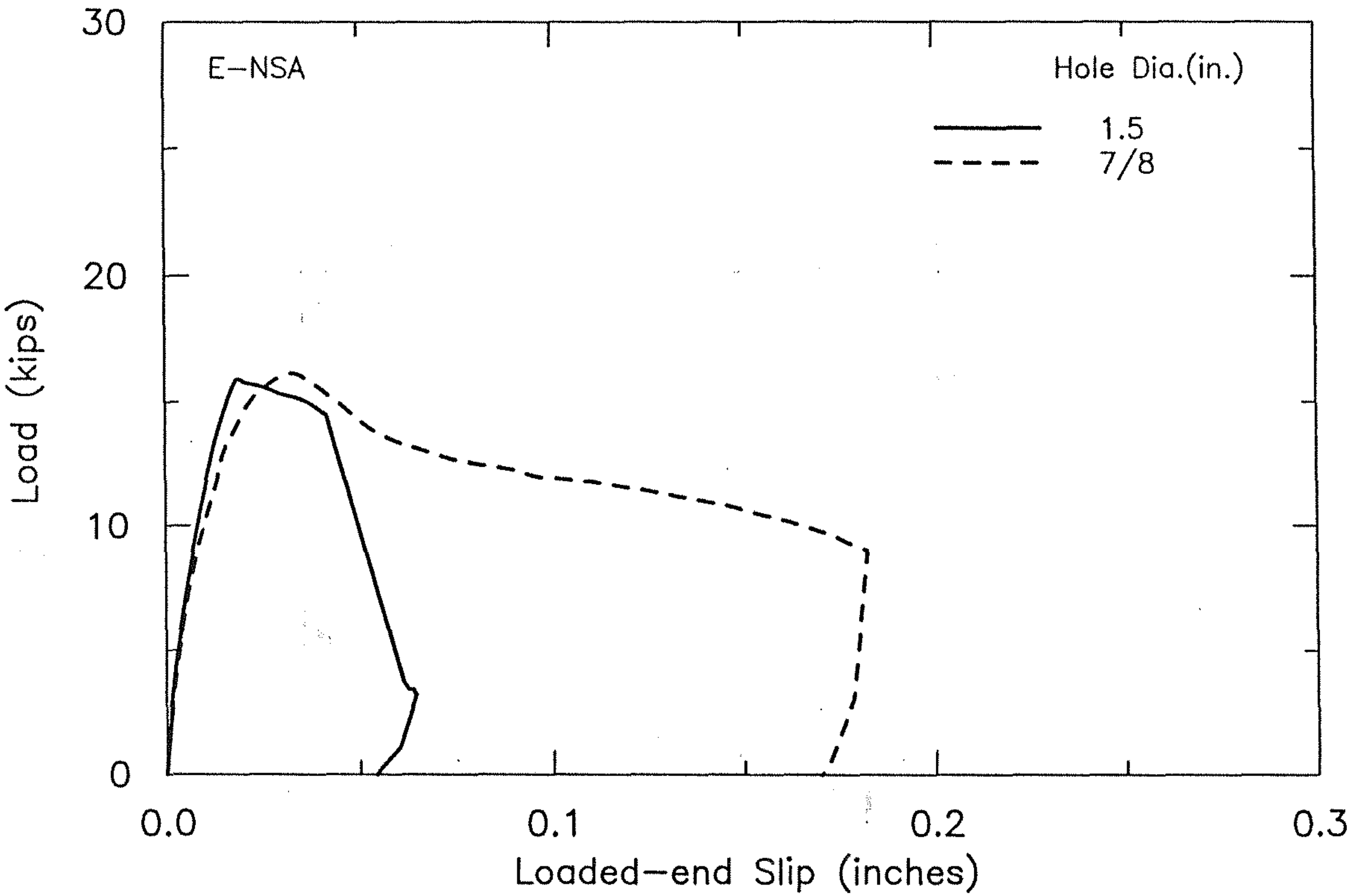

Fig. 2.15 Load-Slip Curves for Vertical NSA Grouted Epoxy-coated No. 5 Bars with ℓ_e = 6 in. and hole diameters of $^7/_8$ and 1.5 in. (Group 5)

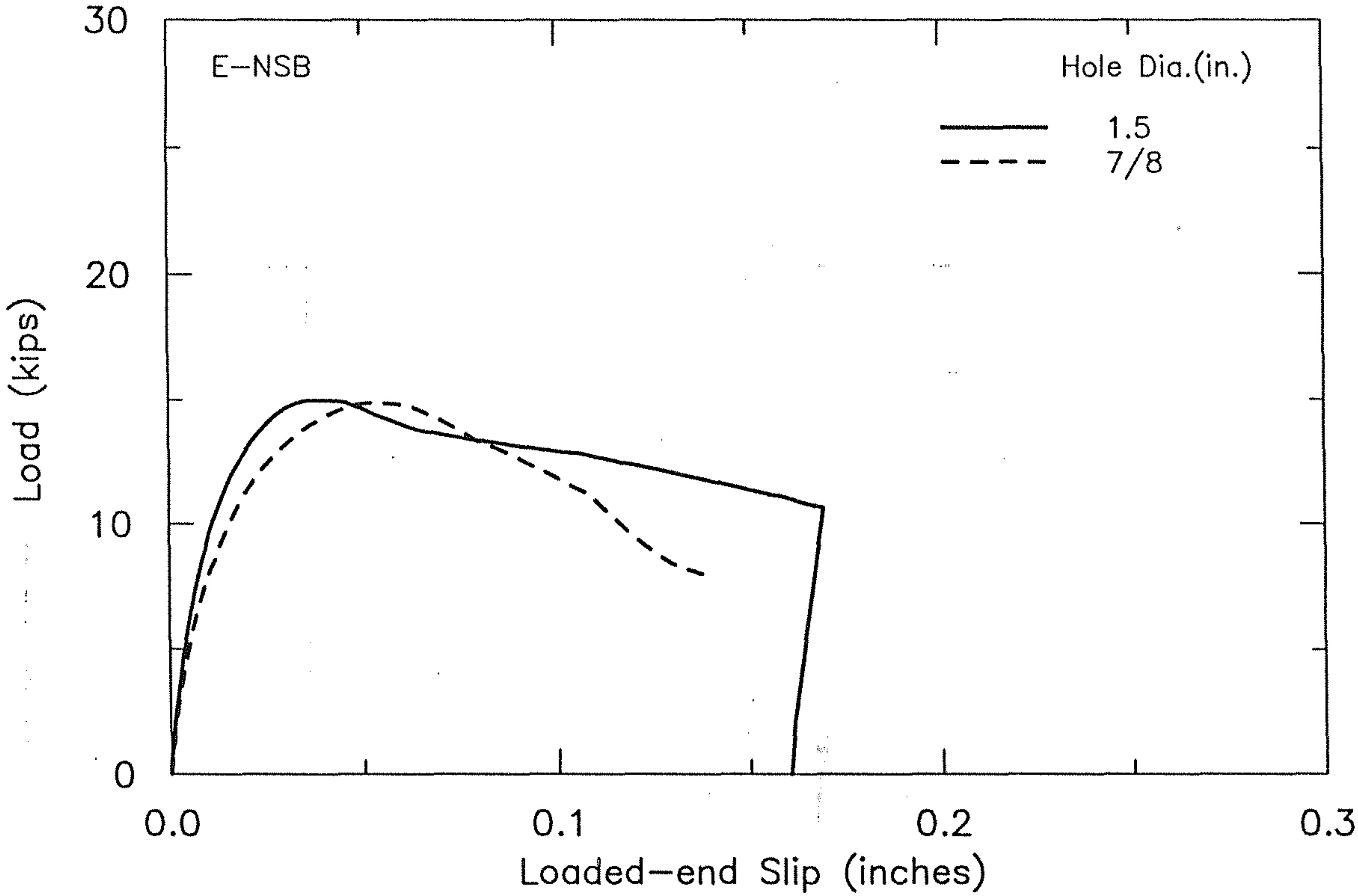

Fig. 2.16 Load-Slip Curves for Vertical NSB Grouted Epoxy-coated No. 5 Bars with $\ell_e = 6$ in. and hole diameters of 7/8 and 1.5 in. (Group 4)

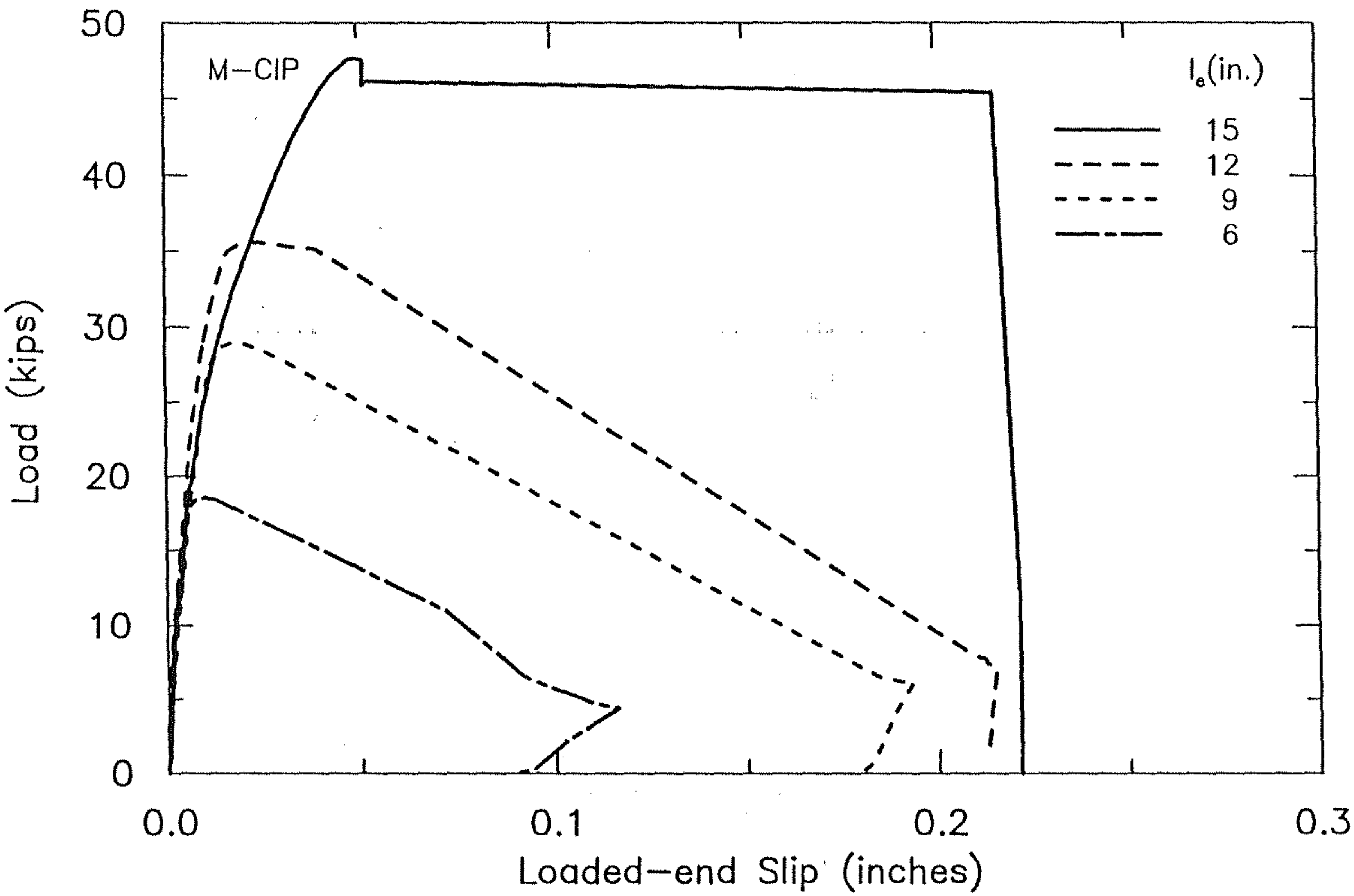

Fig. 2.17 Load-Slip Curves for Vertical Cast-in-place Uncoated No. 8 bars with ℓ_e = 6, 9, 12, 15 in. (Group 13)

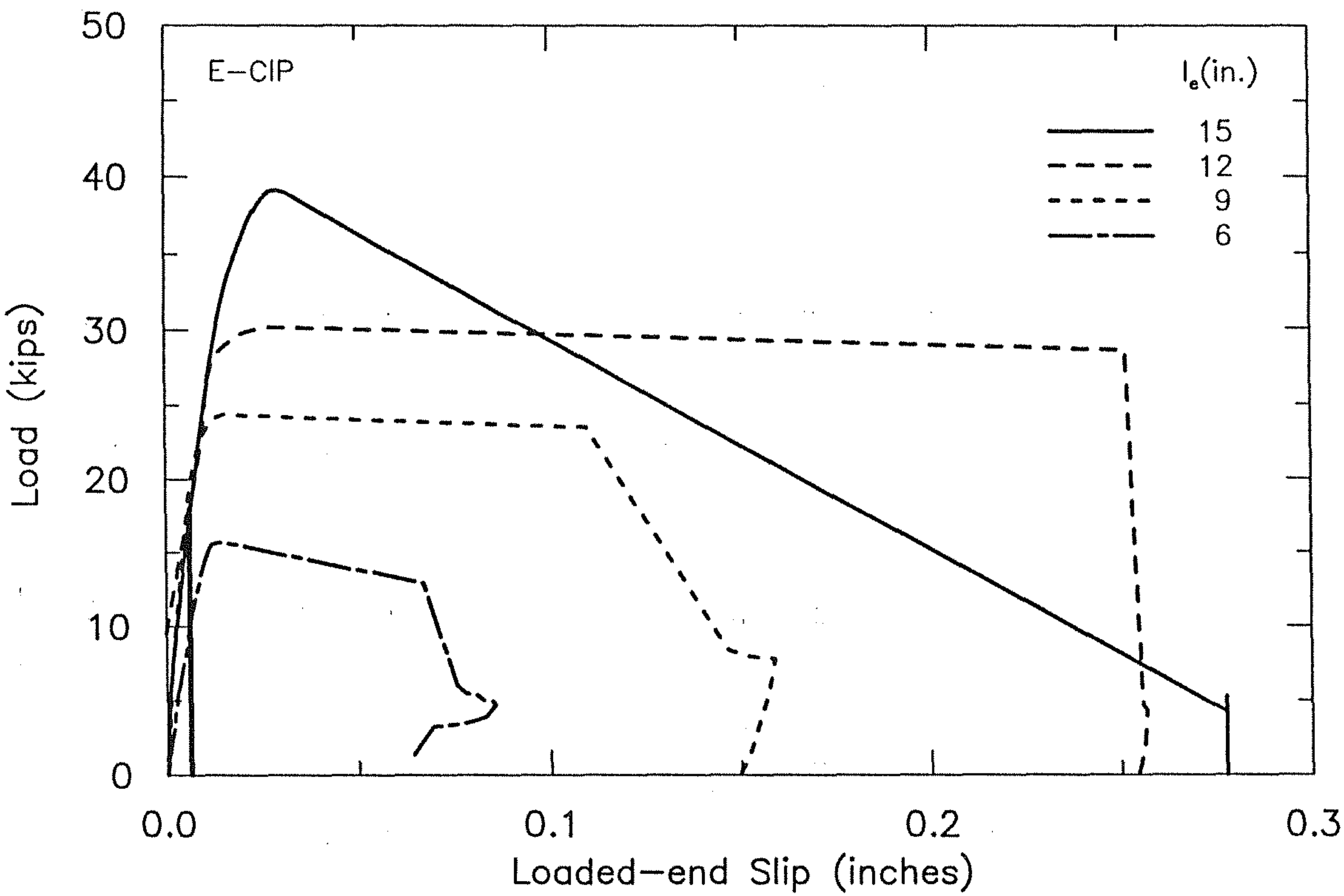

Fig. 2.18 Load-Slip Curves for Vertical Cast-in-place Epoxy-coated No. 8 bars with ℓ_e = 6, 9, 12, 15 in. (Group 13)

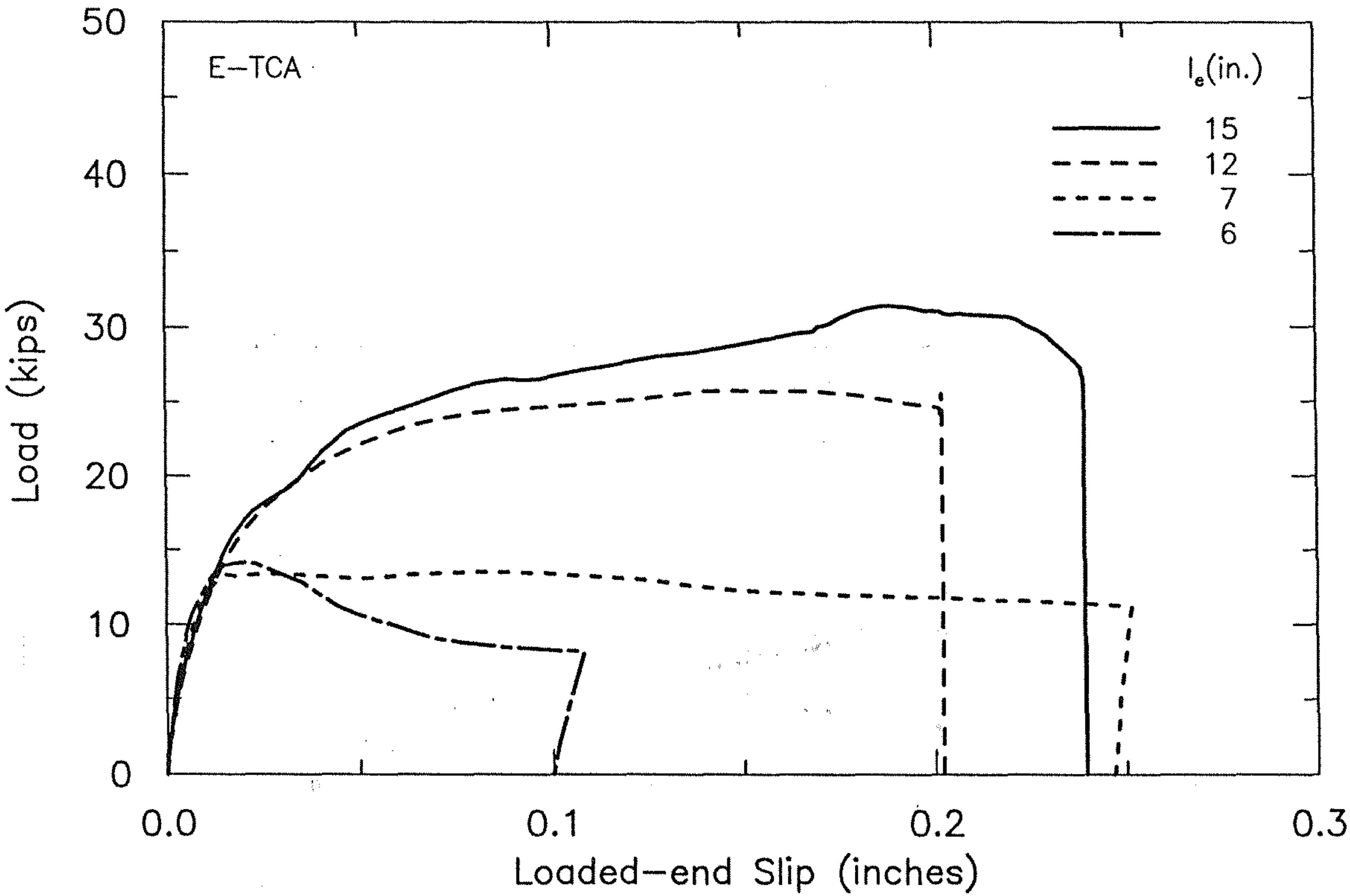

Fig. 2.19 Load-Slip Curves for Vertical TCA Grouted Epoxy-coated No. 8 bars with ℓ_e = 6, 9, 12, 15 in. (Group 13)

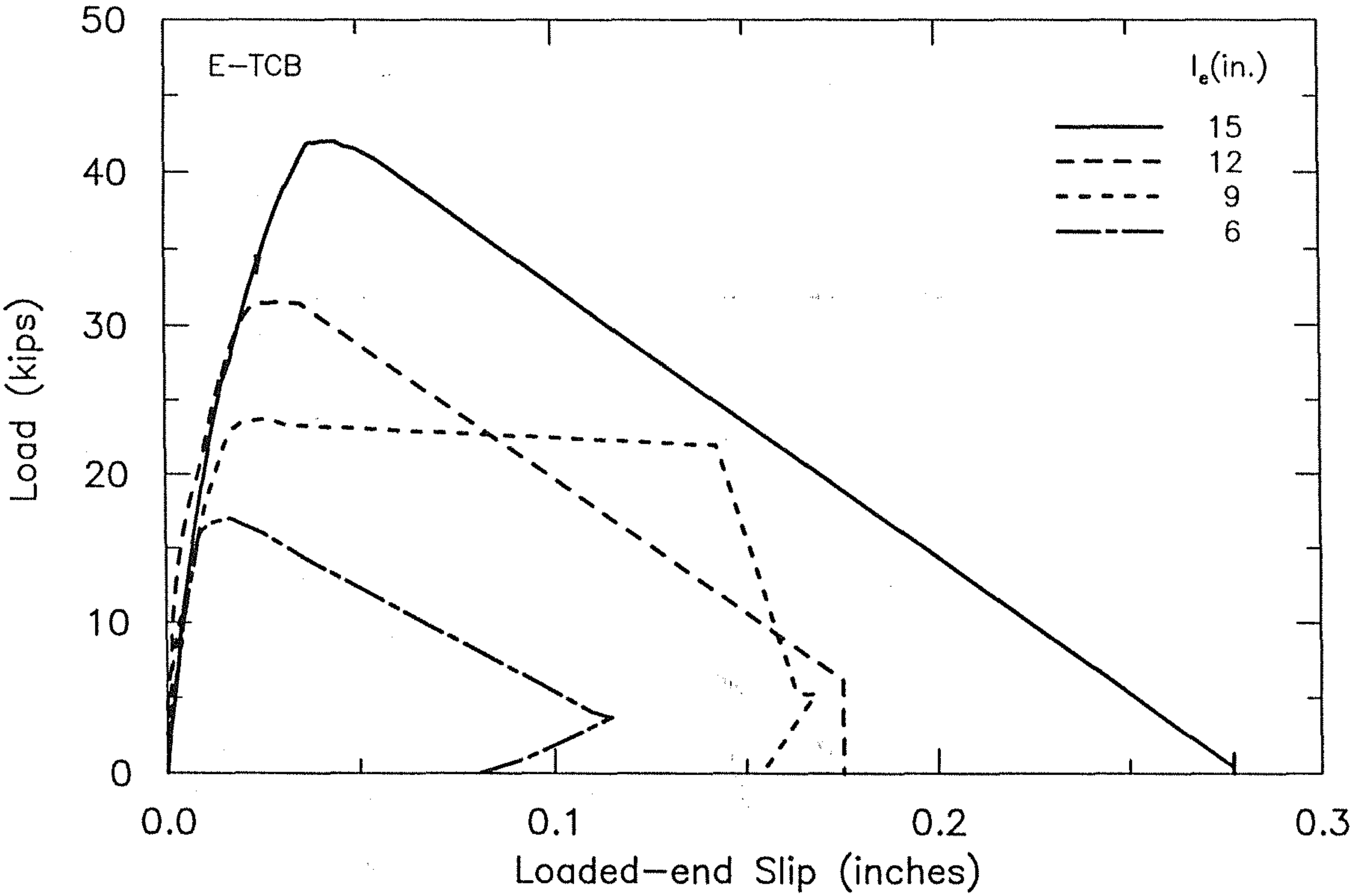

Fig. 2.20 Load-Slip Curves for Vertical TCB Grouted Epoxy-coated No. 8 bars with ℓ_e = 6, 9, 12, 15 in. (Group 13)

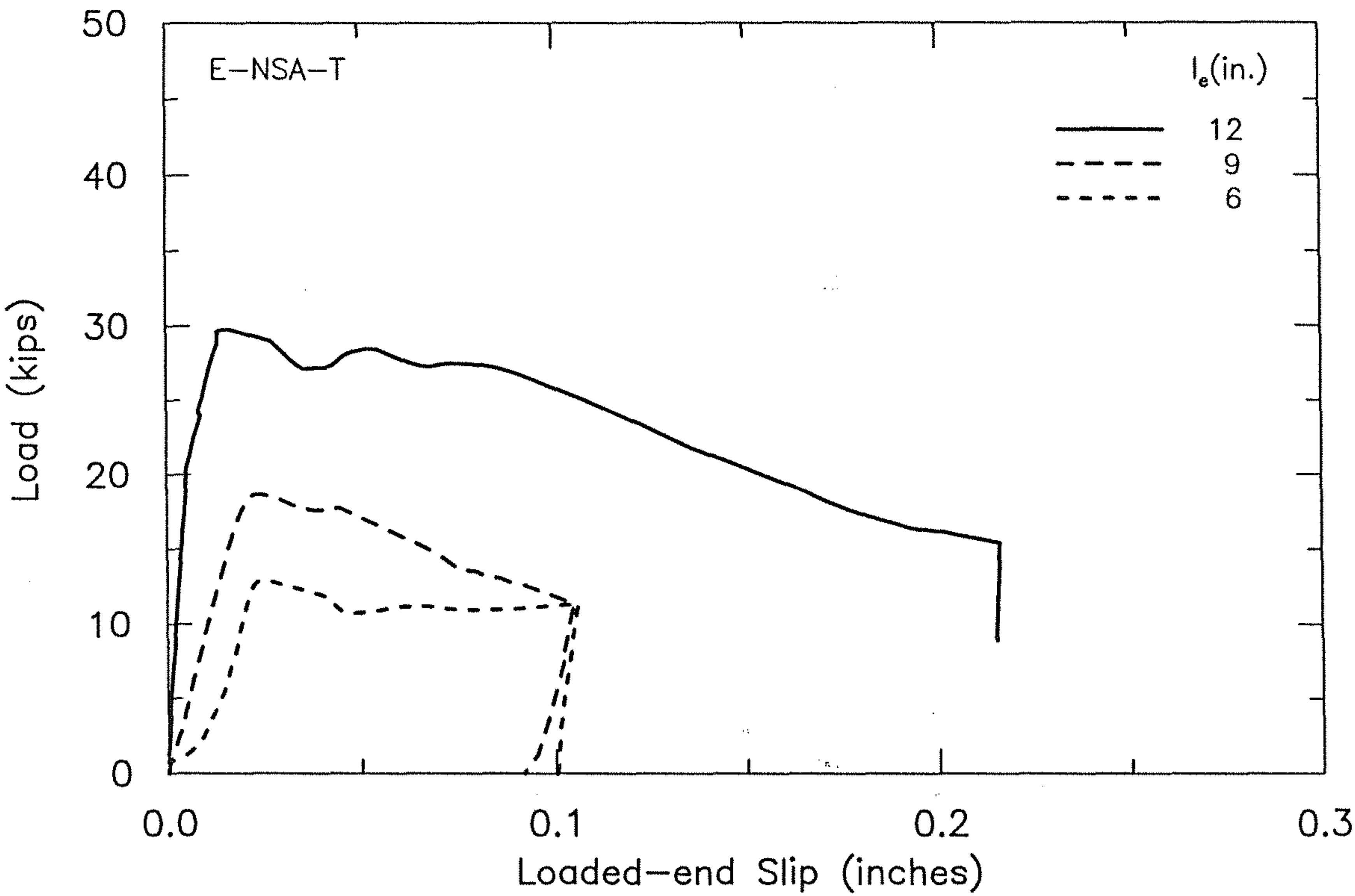

Fig. 2.21 Load-Slip Curves for Horizontal Top-cast NSA Grouted Epoxy-coated No. 8 bars with ℓ_e = 6, 9, 12 in. (Group 18)

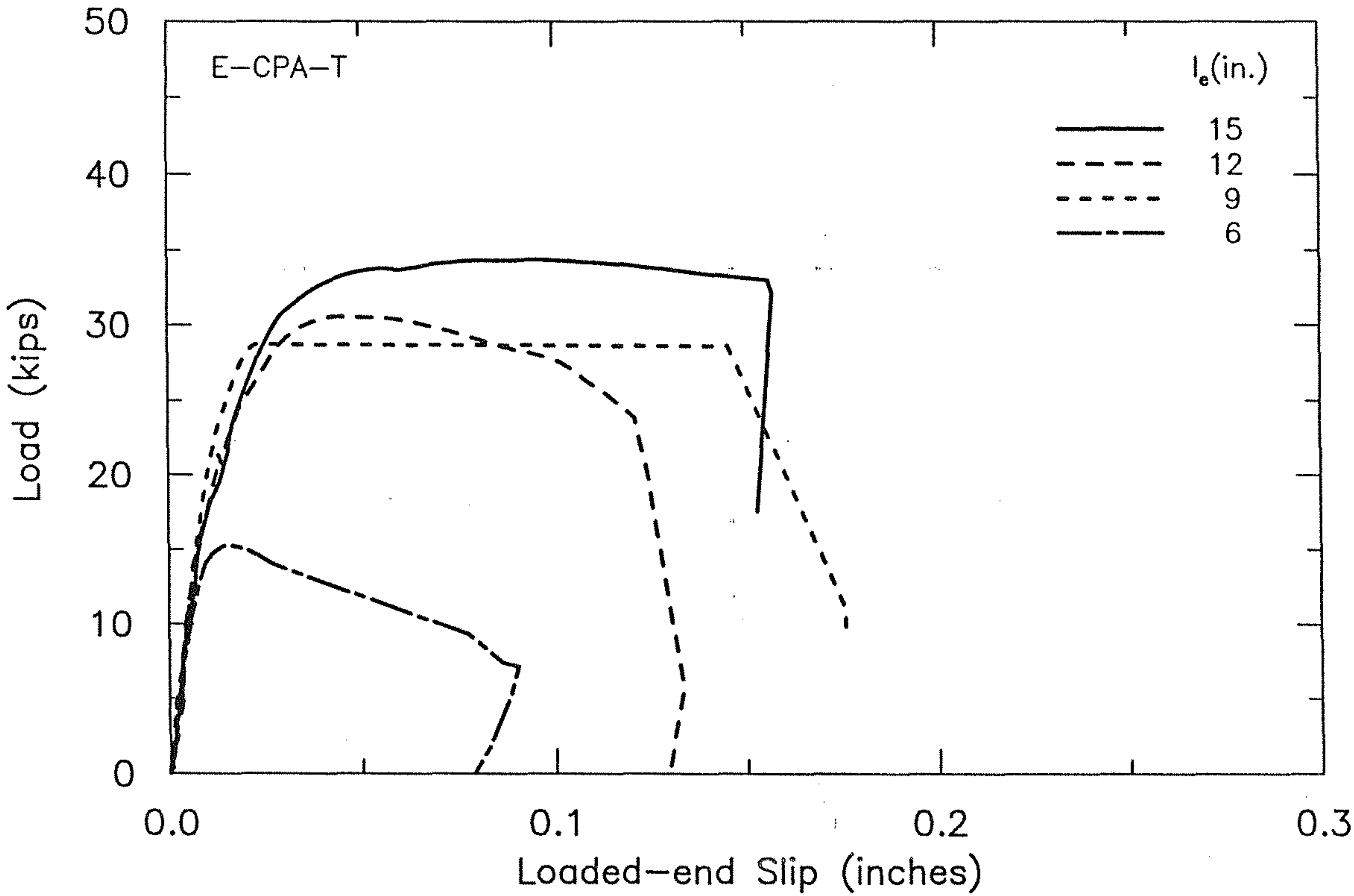

Fig. 2.22 Load-Slip Curves for Horizontal Top-cast CPA Grouted Epoxy-coated No. 8 bars with ℓ_e = 6, 9, 12 and 15 in. (Group 20)

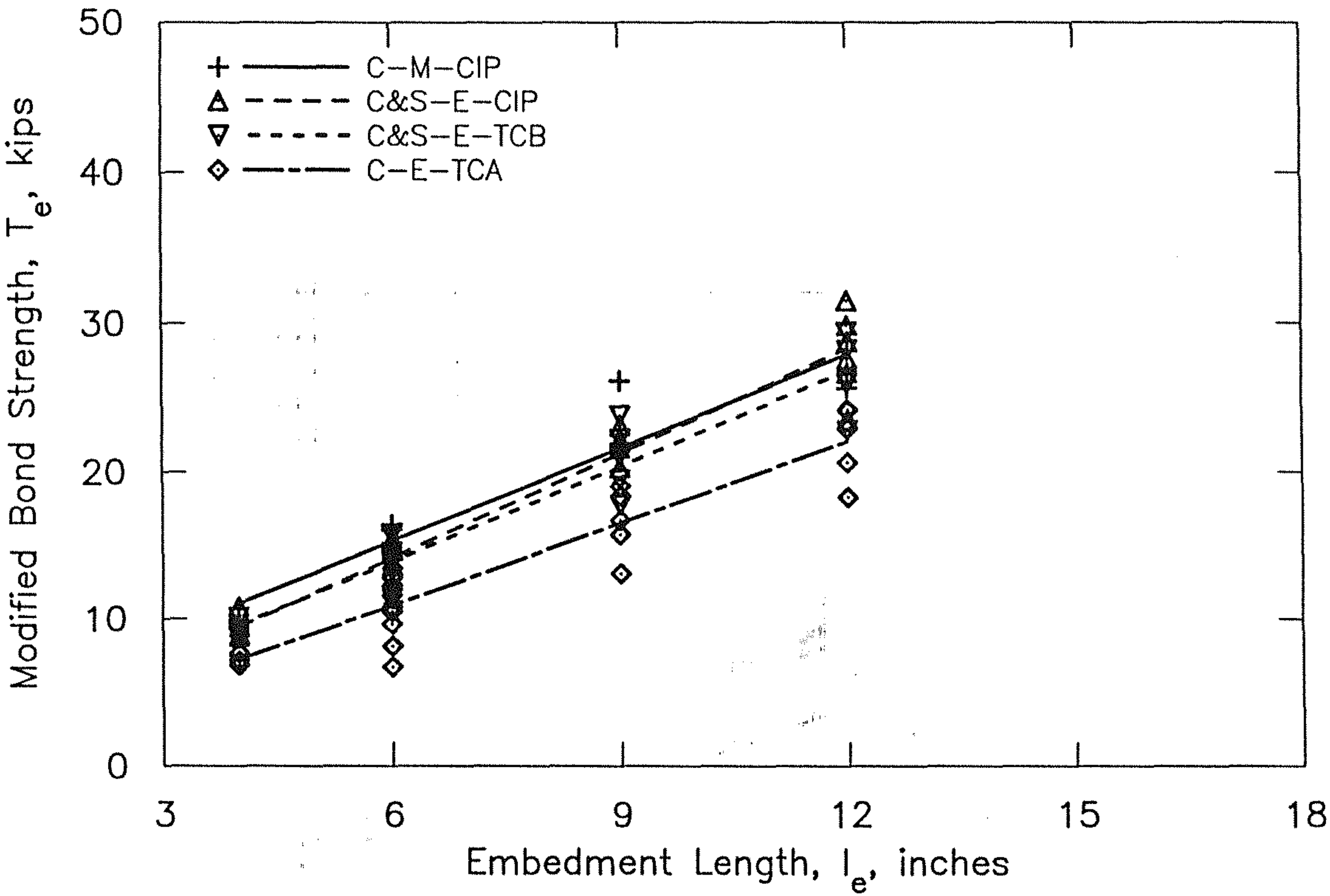

Fig. 3.1 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for C and S Patterns, Cast-in-place and Grouted No. 5 bars (Groups 11, 15-17, 22)

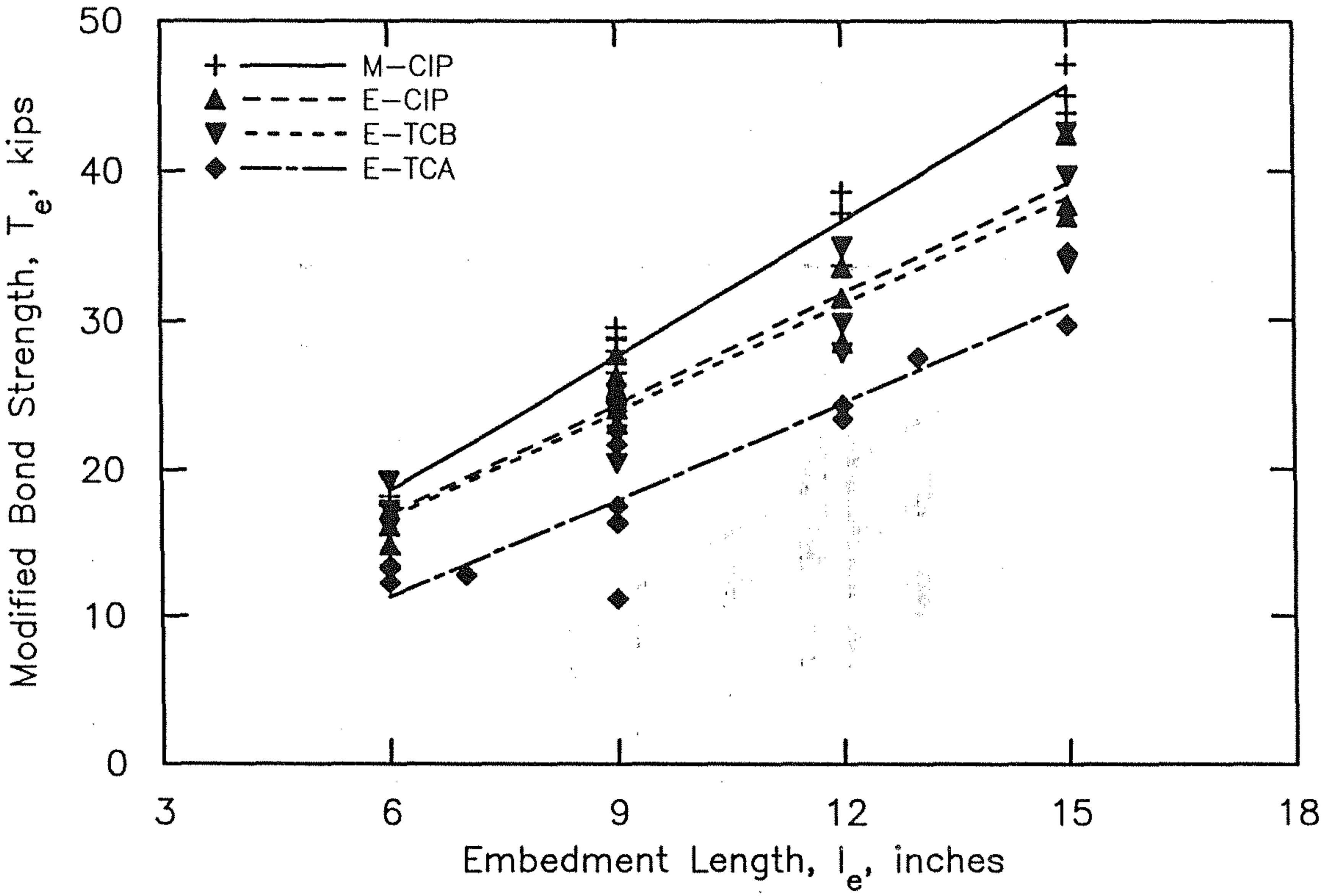

Fig. 3.2 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for Cast-in-place and Grouted No. 8 bars (Groups 8-10, 12-14)

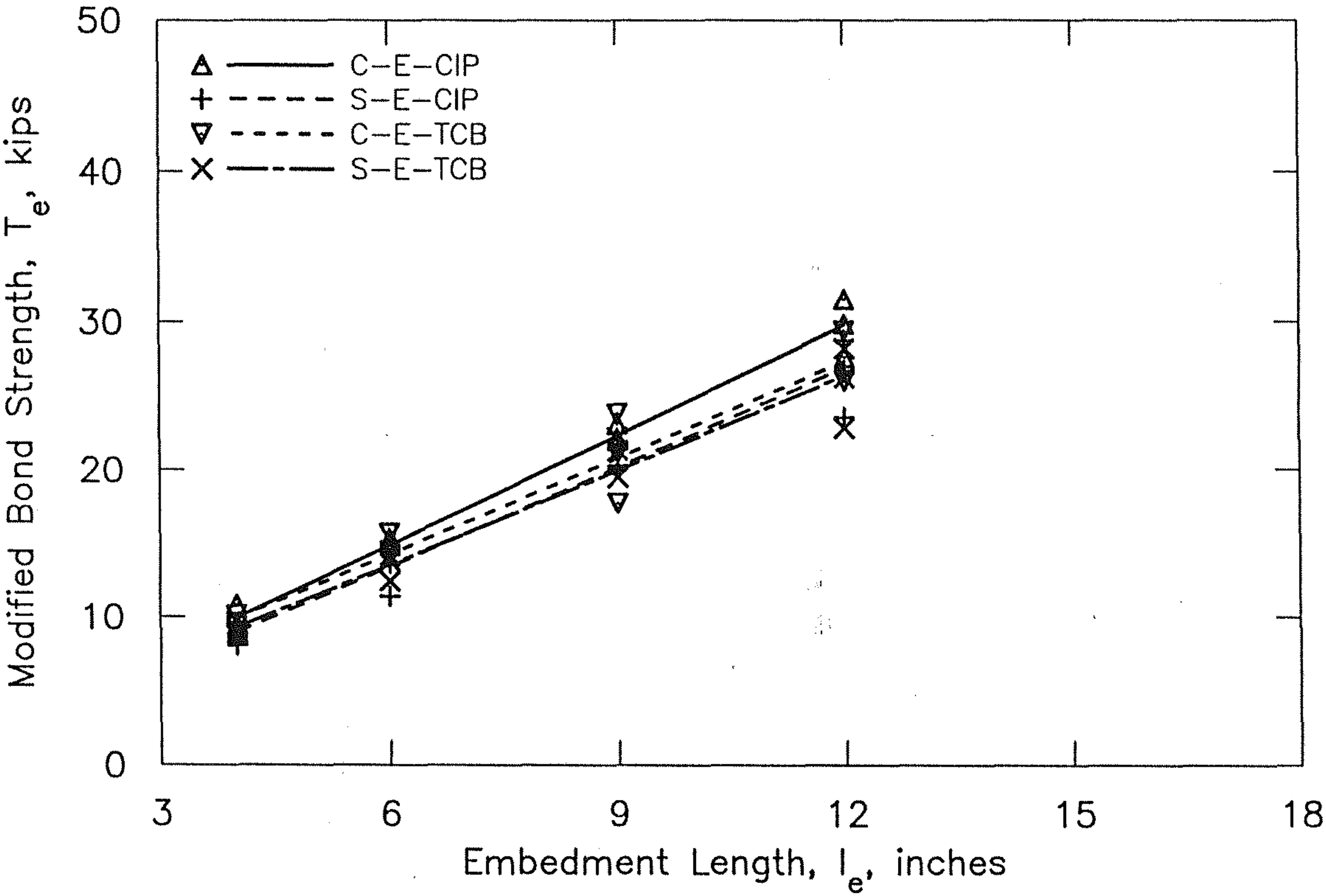

Fig. 3.3 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for C and S Patterns, Cast-in-place and TCB Grouted No. 5 Bars (Groups 15-17)

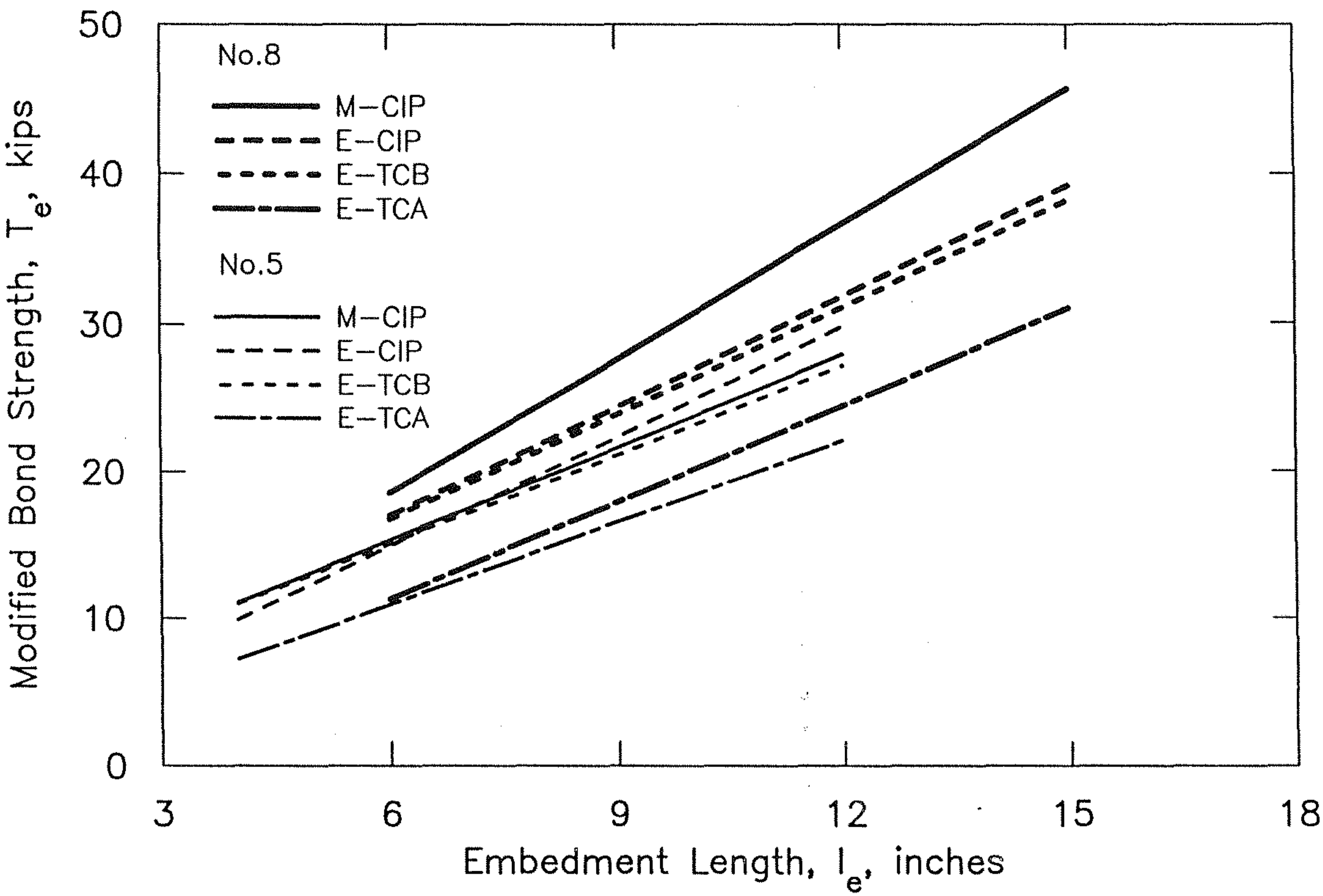

Fig. 3.4 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e. Best-fit lines for No. 8 bars (Groups 8-10, 12-14) and No. 5 bars (Groups 11, 15-17, 22)

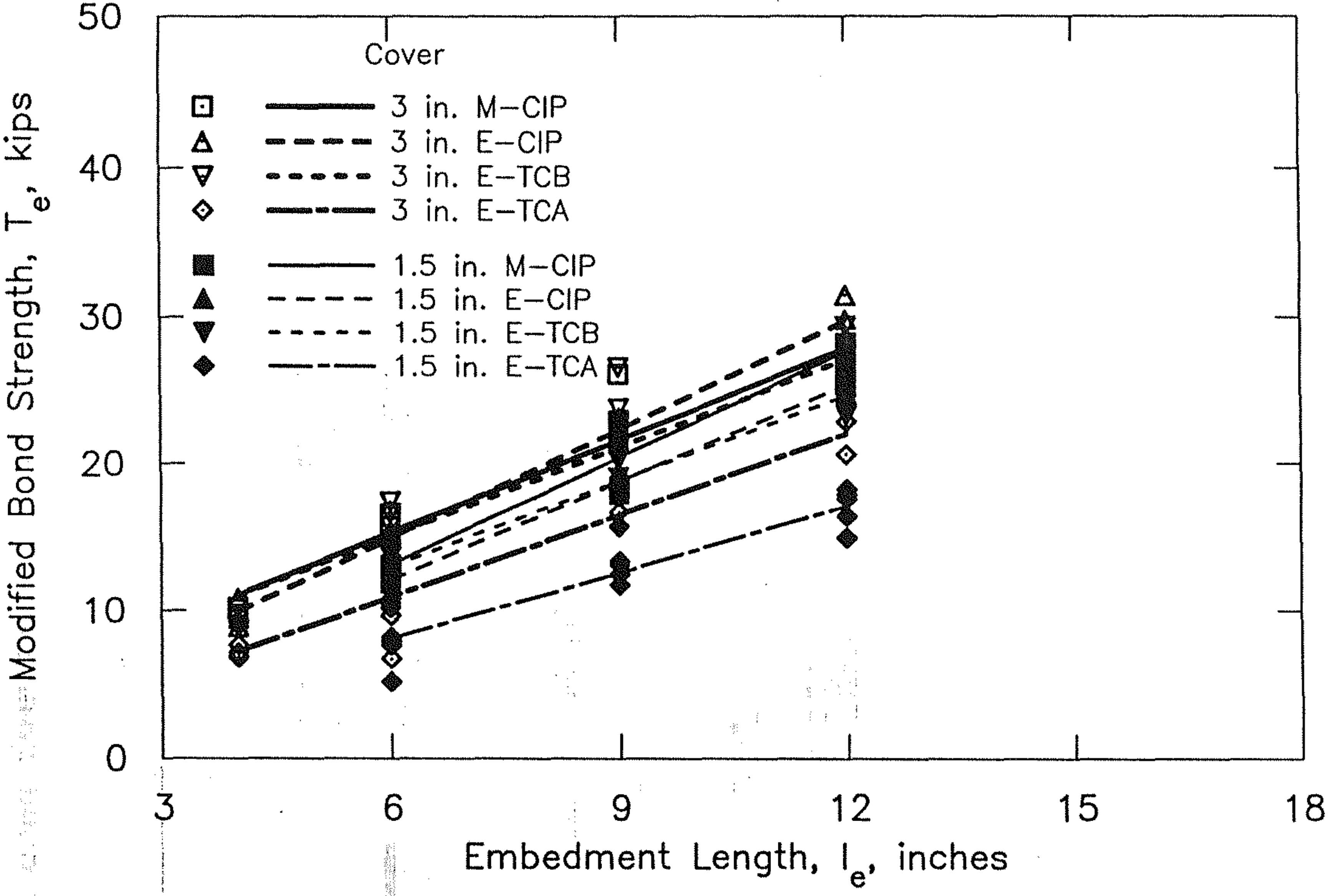

Fig. 3.5 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e for Cast-in-place and Grouted No. 5 bars with 1.5 in. Cover (Groups 19, 22) and 3 in. Cover (Groups 11, 15-17, 22)

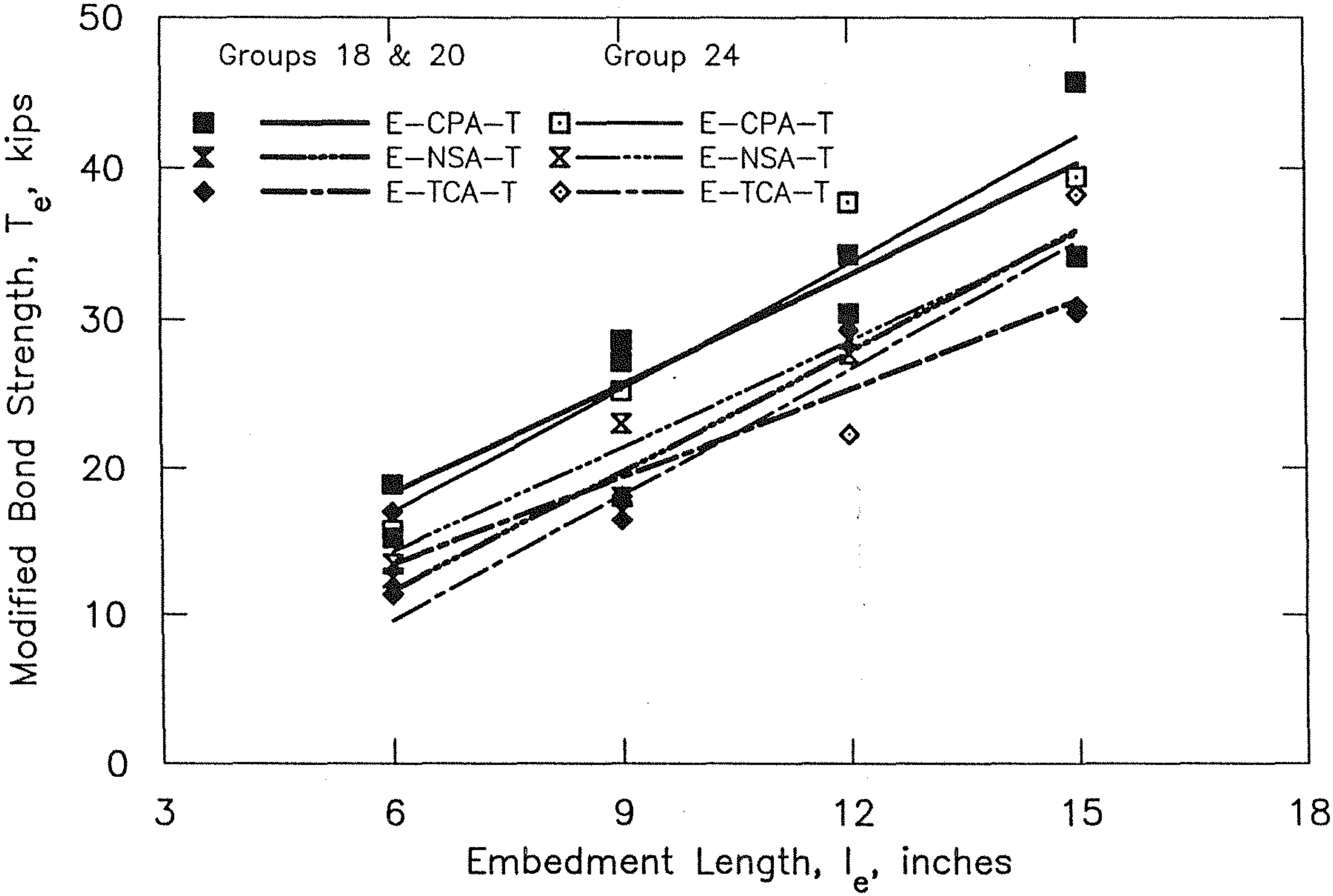

Fig. 3.6 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e for Horizontal Top-cast Grouted No. 8 Bars, Comparing Bars in Groups 18 and 20 (compression bearing plate $4^1/_2$ in. away from center of test bar) to Bars in Group 24 (compression bearing plate 12 in. away from center of test bar)

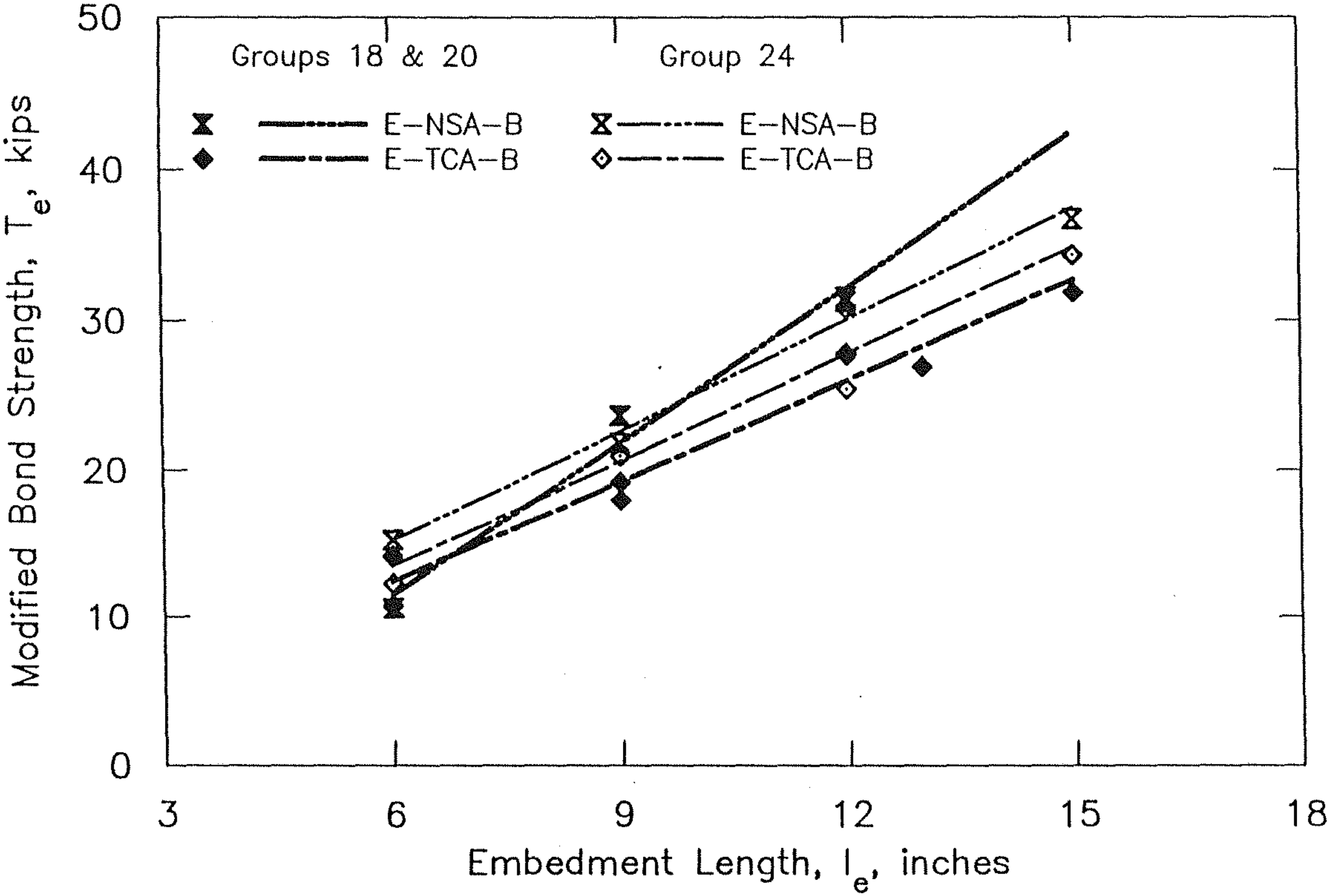

Fig. 3.7 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for Horizontal Bottom-cast Grouted No. 8 Bars, Comparing Bars in Groups 18 and 20 (compression bearing plate $4^1/_2$ in. away from center of test bar) to Bars in Group 24 (compression bearing plate 12 in. away from center of test bar)

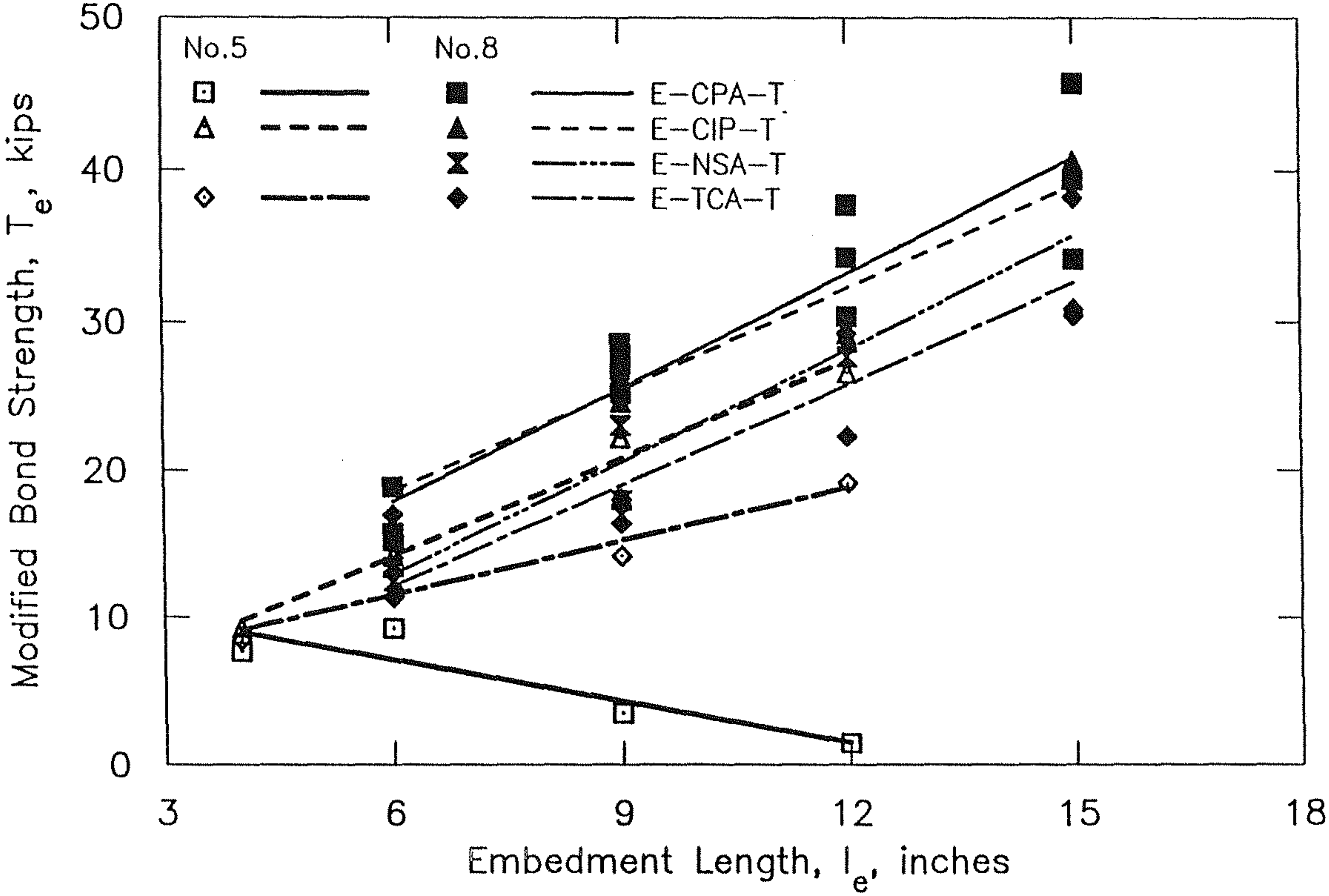

Fig. 3.8 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for Horizontal Top-cast No. 5 (Group 21) and No. 8 (Groups 18, 20, 24) Bars

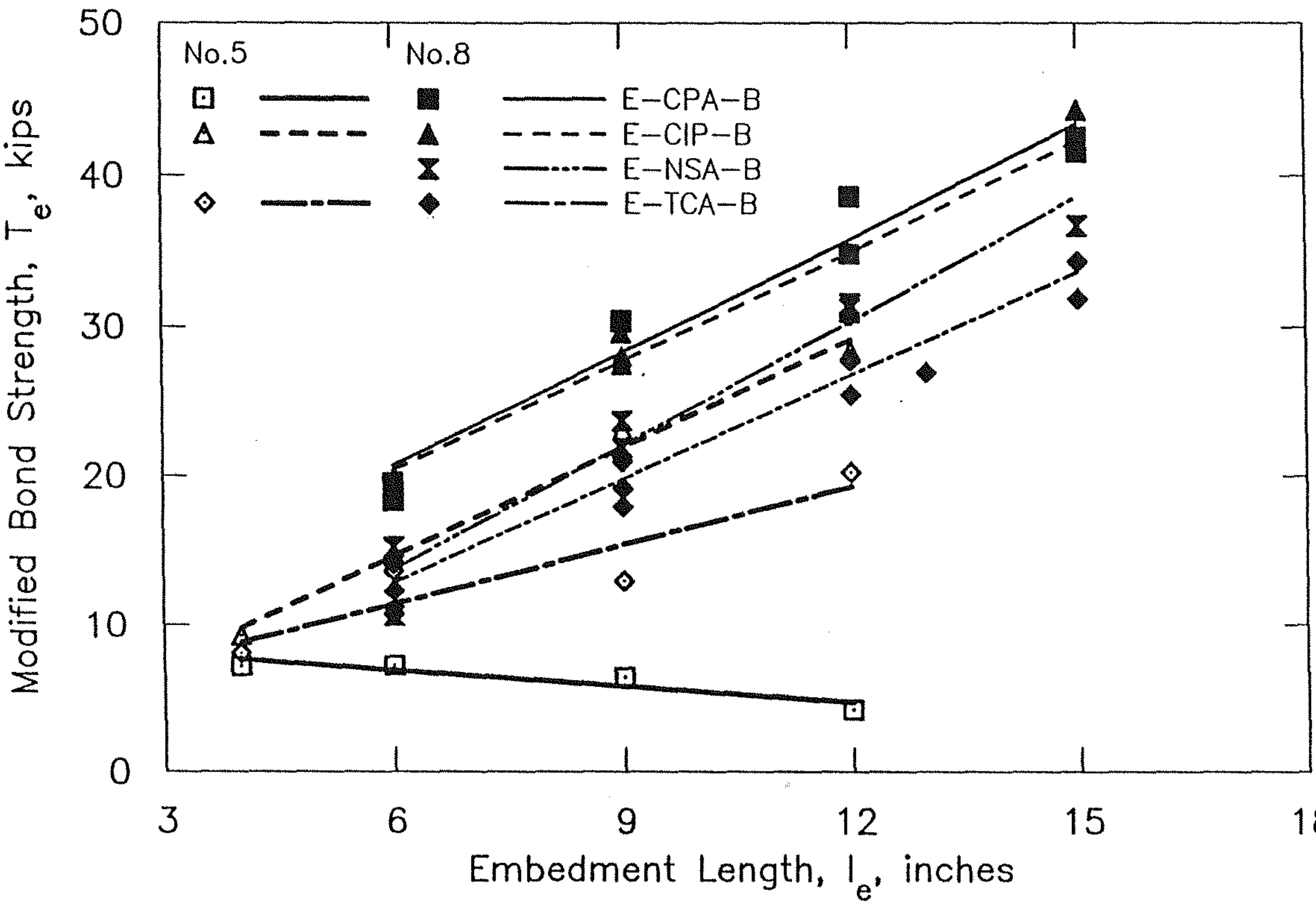

Fig. 3.9 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e for Horizontal Bottom-cast No. 5 (Group 21) and No. 8 (Groups 18, 20, 24) Bars

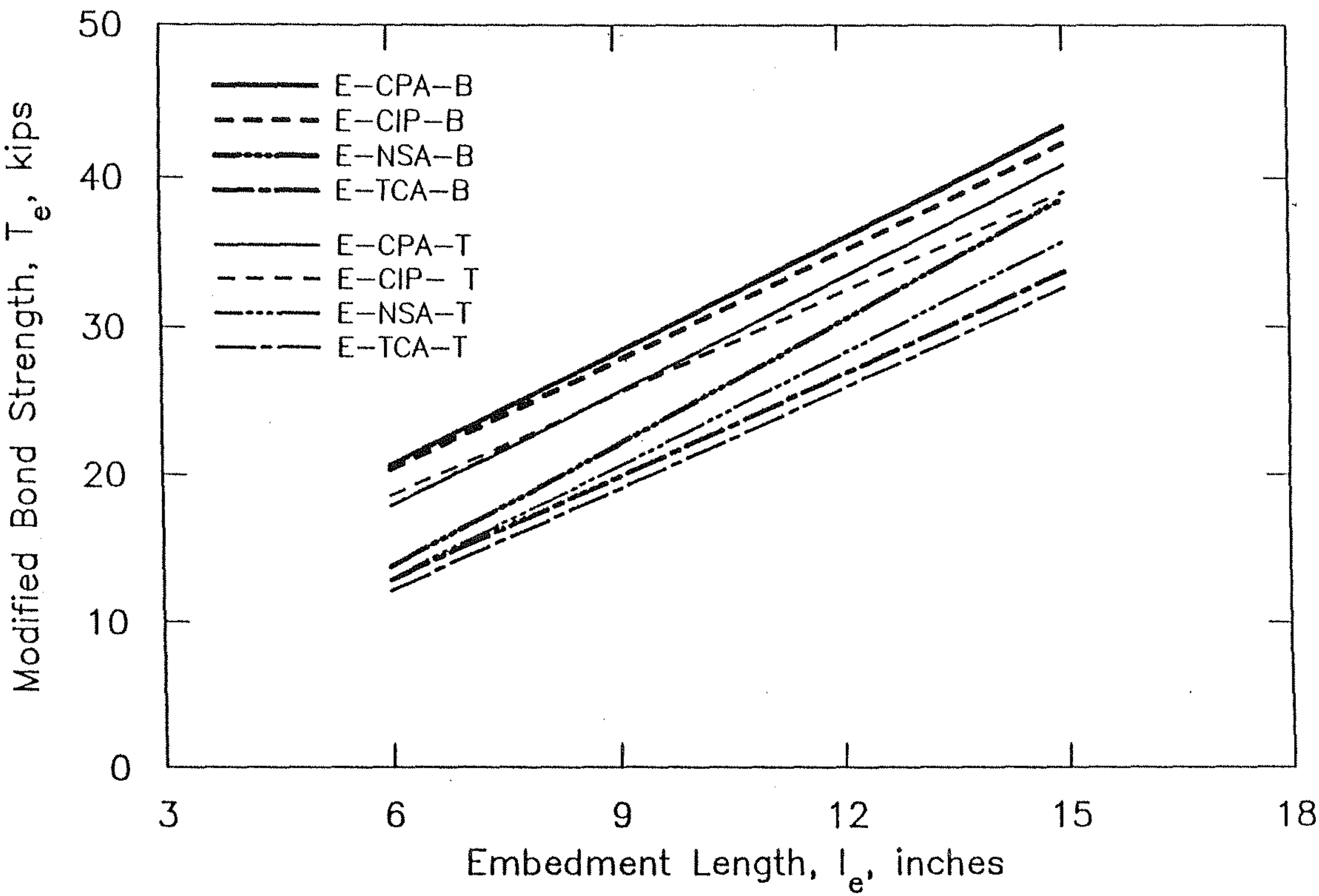

Fig. 3.10 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e. Best-fit Lines for Horizontal Bottom-cast and Top-Cast No. 8 Bars (Groups 18, 20, 24)

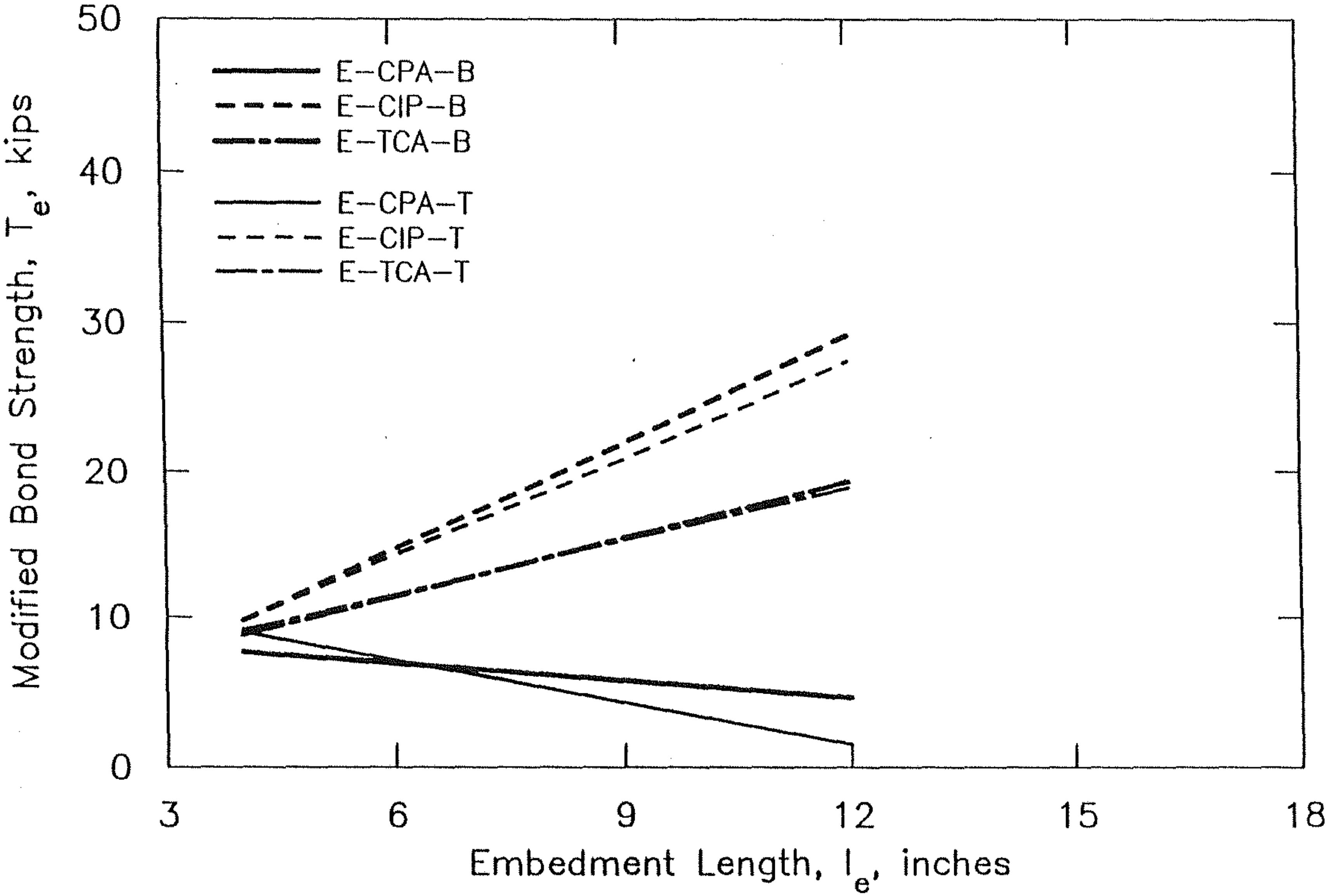

Fig. 3.11 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for Horizontal Bottom-cast and Top-Cast No. 5 Bars (Group 21)

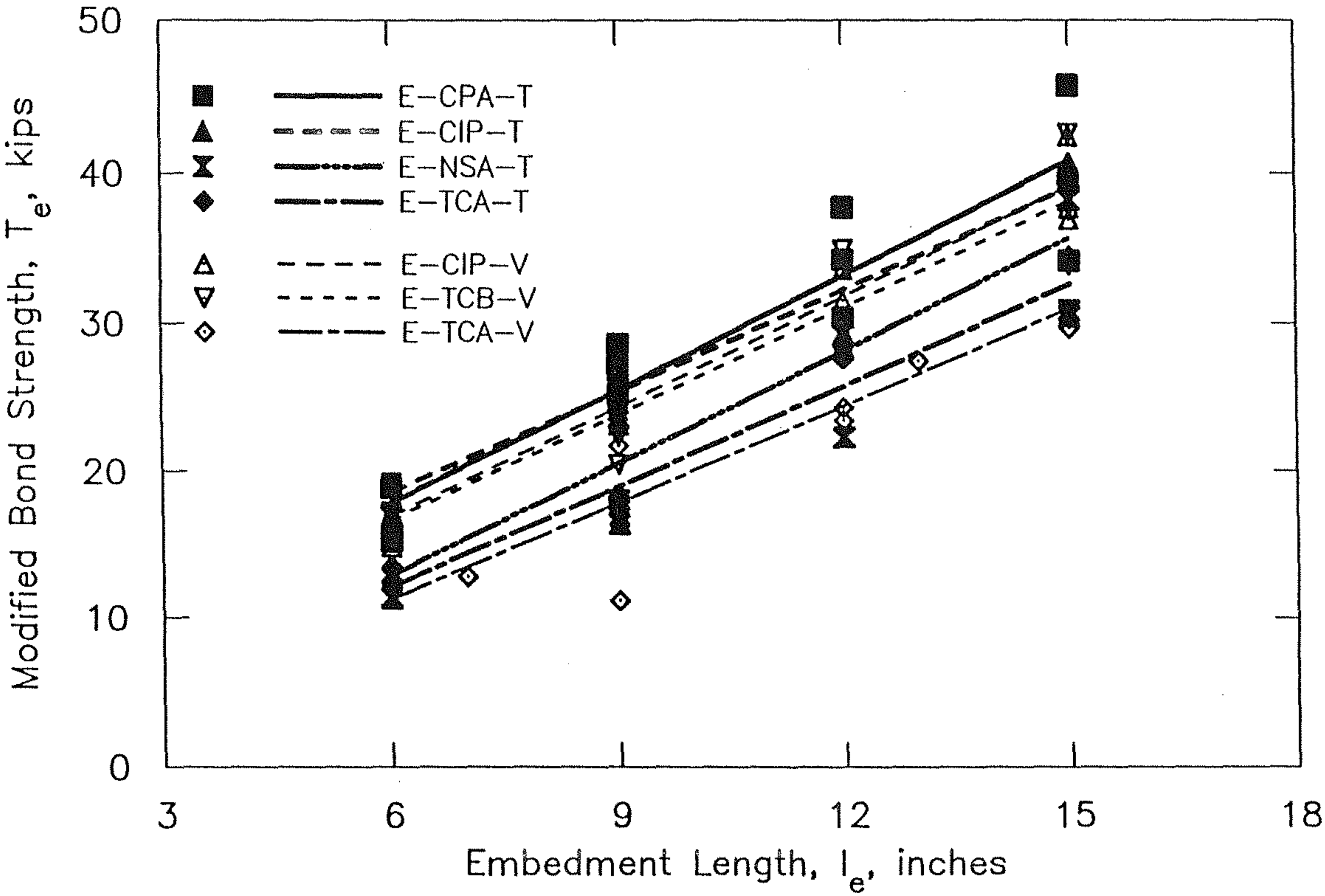

Fig. 3.12 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for Horizontal Top-cast No. 8 Bars (Groups 18-20, 24) and Vertical No. 8 Bars (Groups 8-10, 12-14)

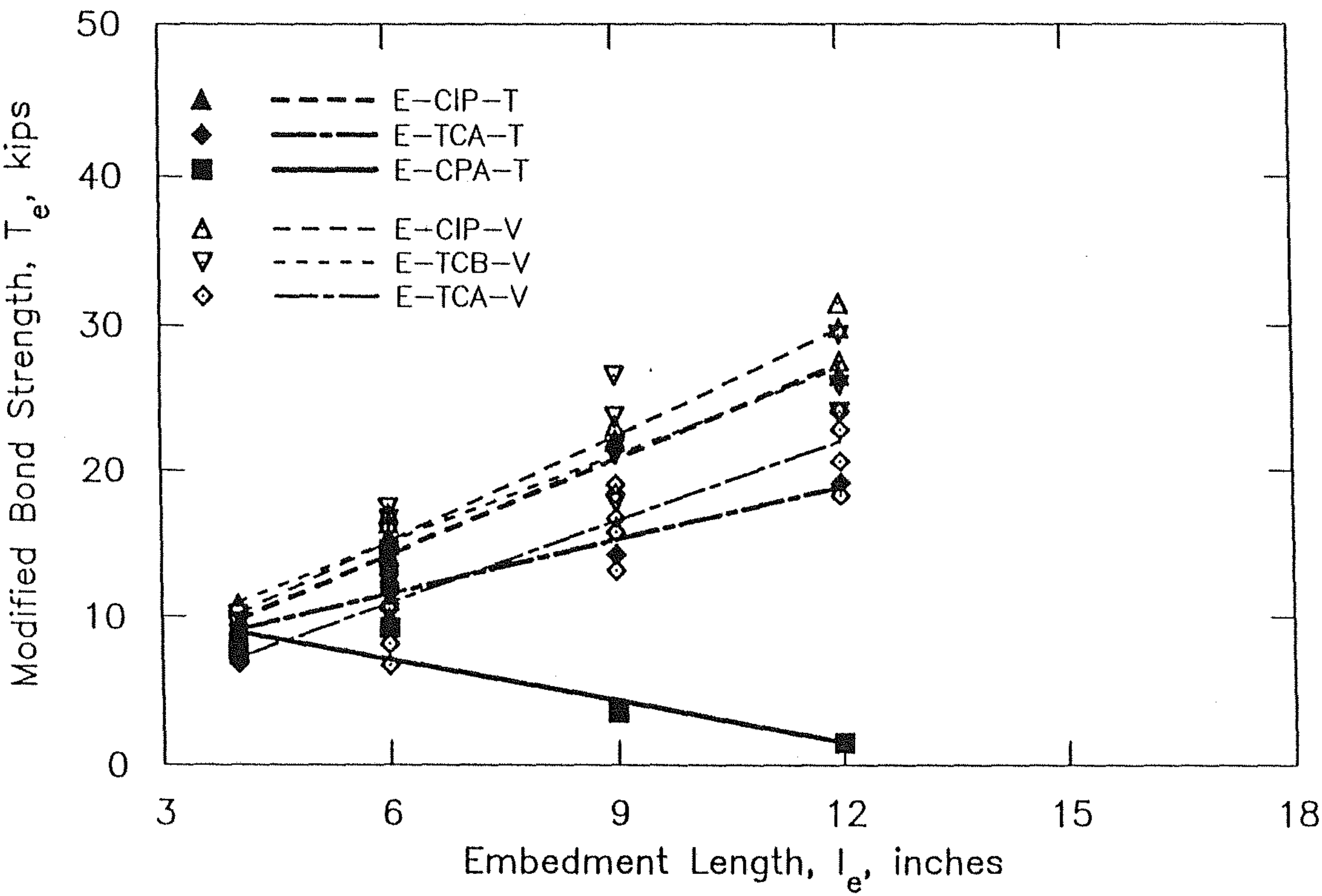

Fig. 3.13 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, Best-fit Lines for Horizontal Top-cast No. 5 Bars (Group 21) and Vertical No. 5 Bars (Groups 11, 15-17, 22)

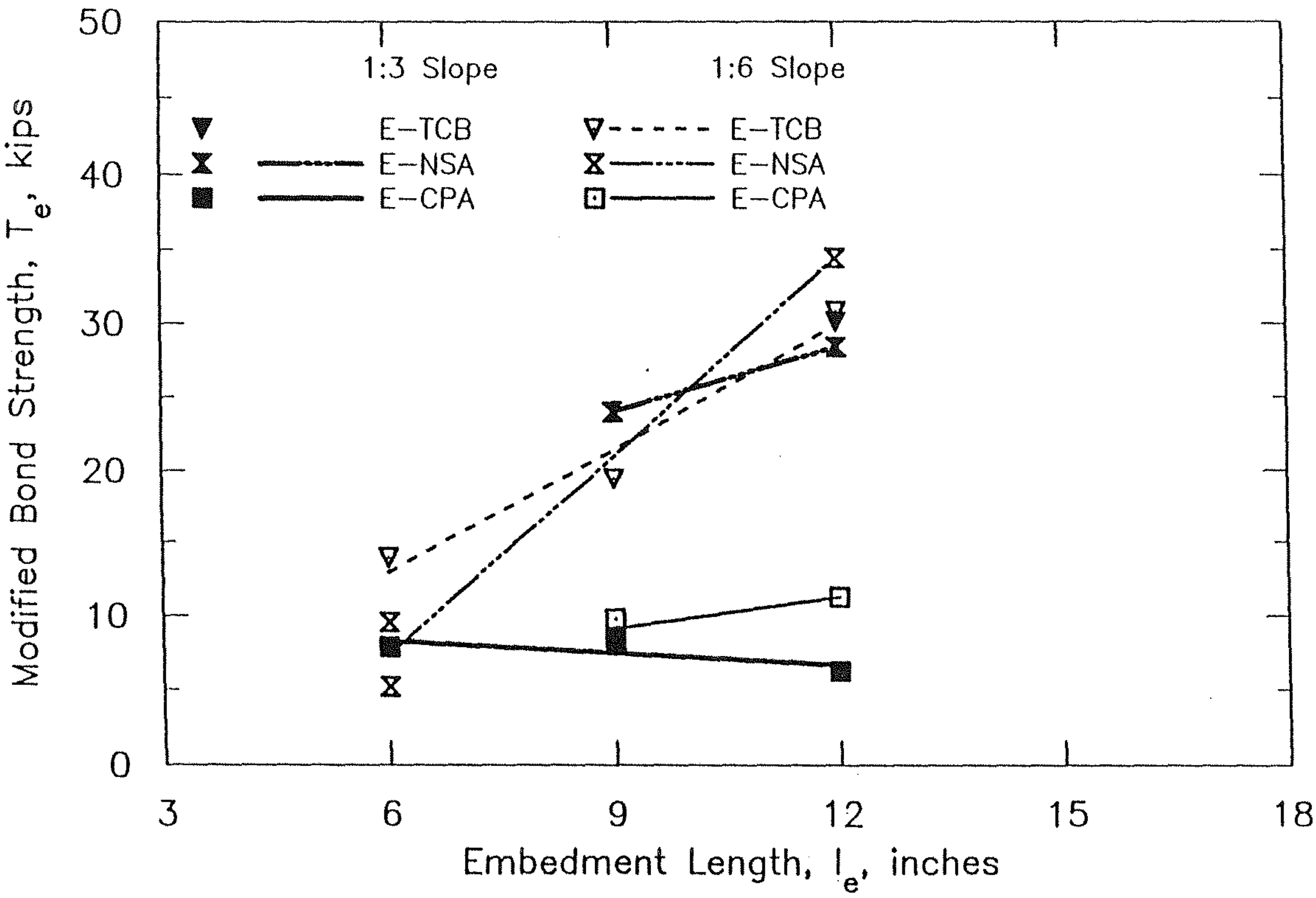

Fig. 3.14 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for Sloped No. 5 bars (Group 24)

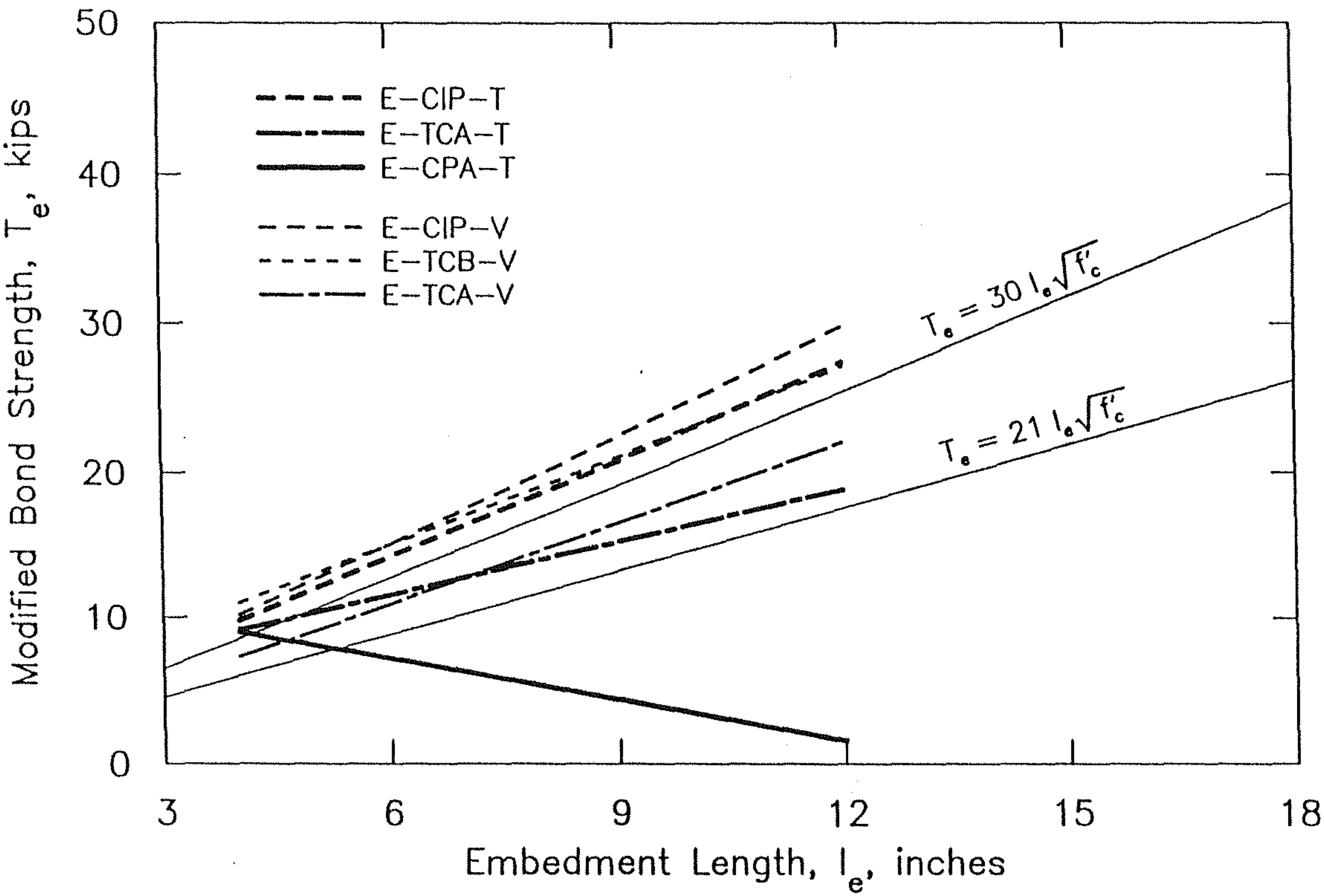

Fig. 4.1 Comparison of Test Results with Expressions Defining Minimum Grout Strength Class Requirements, No. 5 bars, $f'_c = 5000$ psi

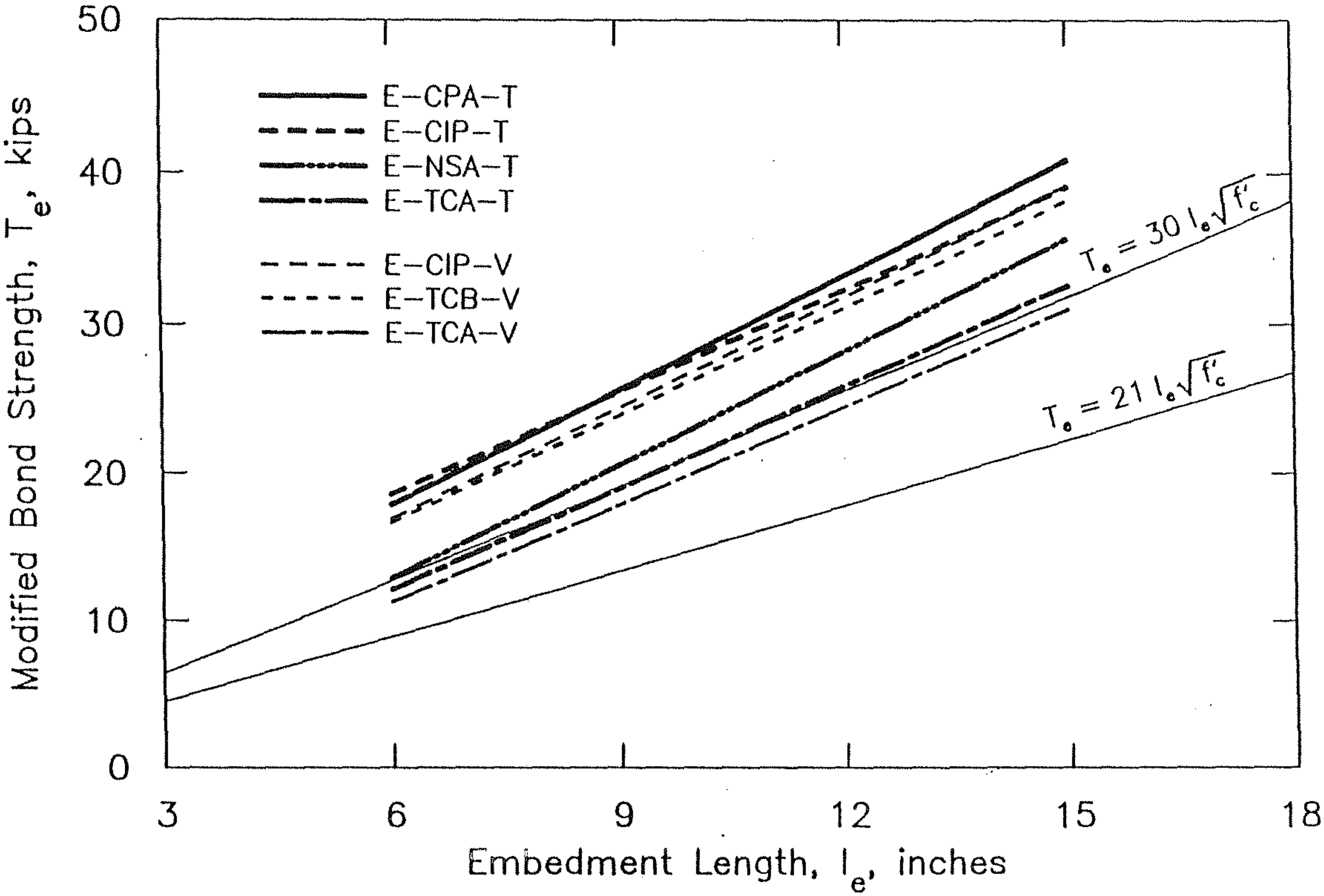

Fig. 4.2 Comparison of Test Results with Expressions Defining Minimum Grout Strength Class Requirements, No. 8 bars, $f'_c = 5000$ psi

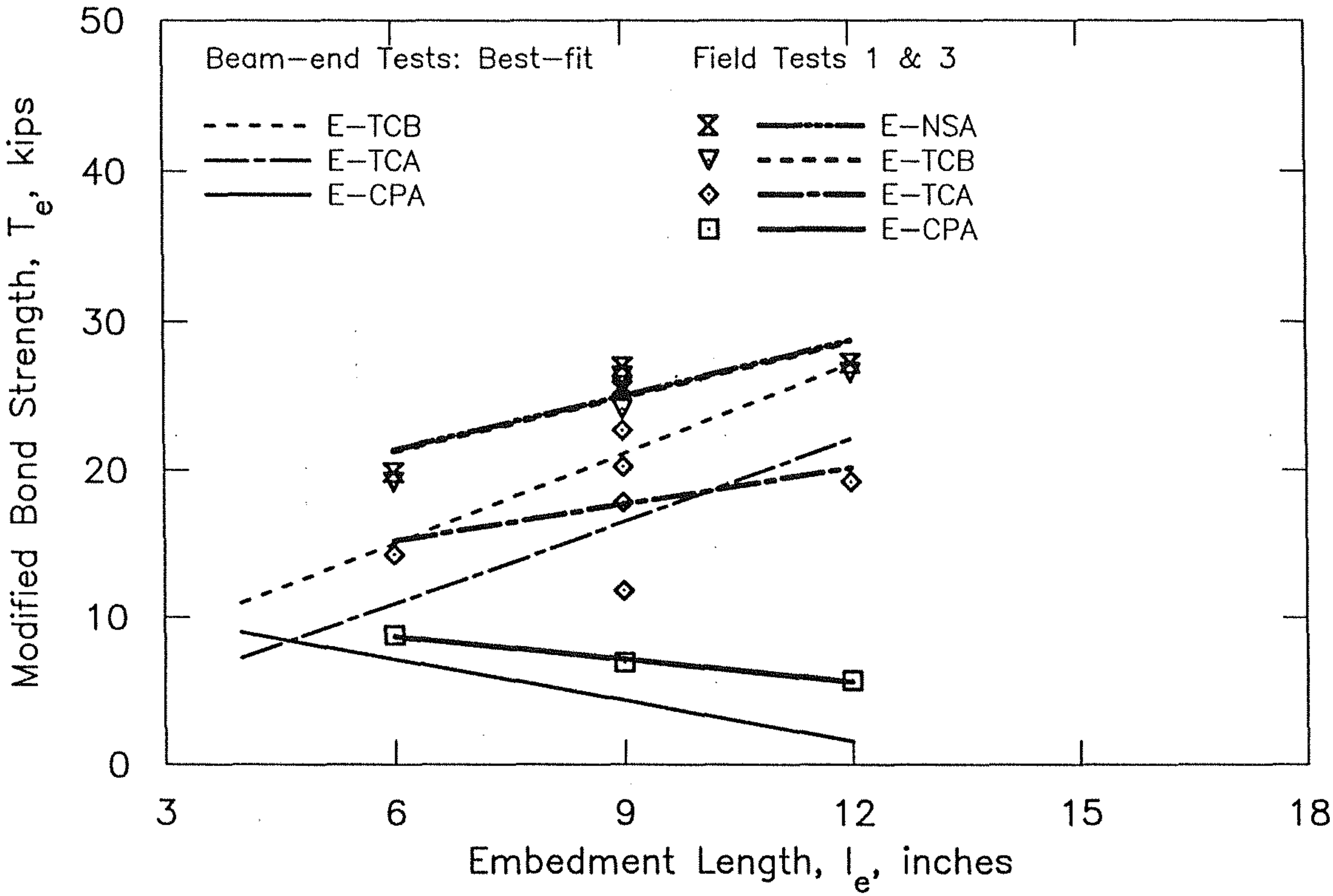

Fig. 5.2 Modified Bond Strength, T_e, versus Embedment Length, ℓ_e, for No. 5 Bars in Field Tests 1 and 3, and Best-fit Lines for Beam-end Tests (Groups 11, 15-17, 22)

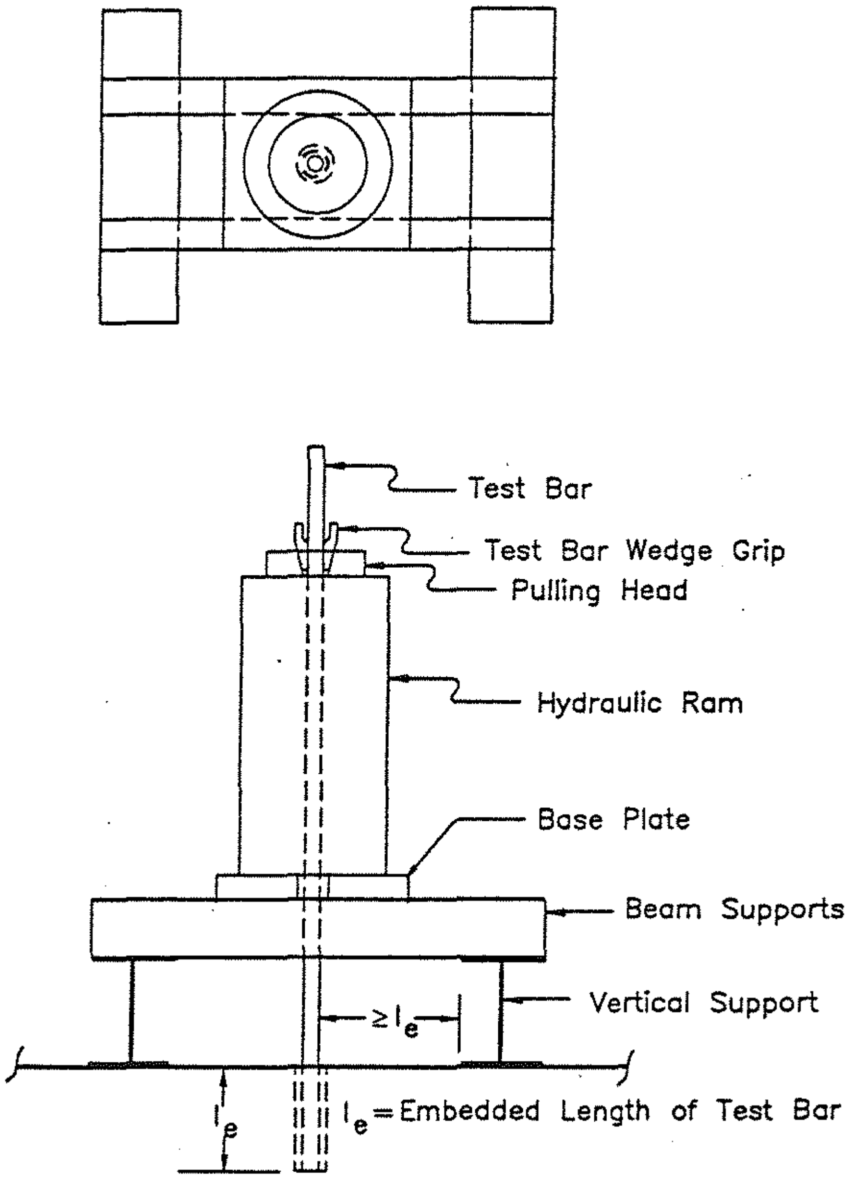

Fig. 5.3 Schematic of Recommended Field Test Apparatus

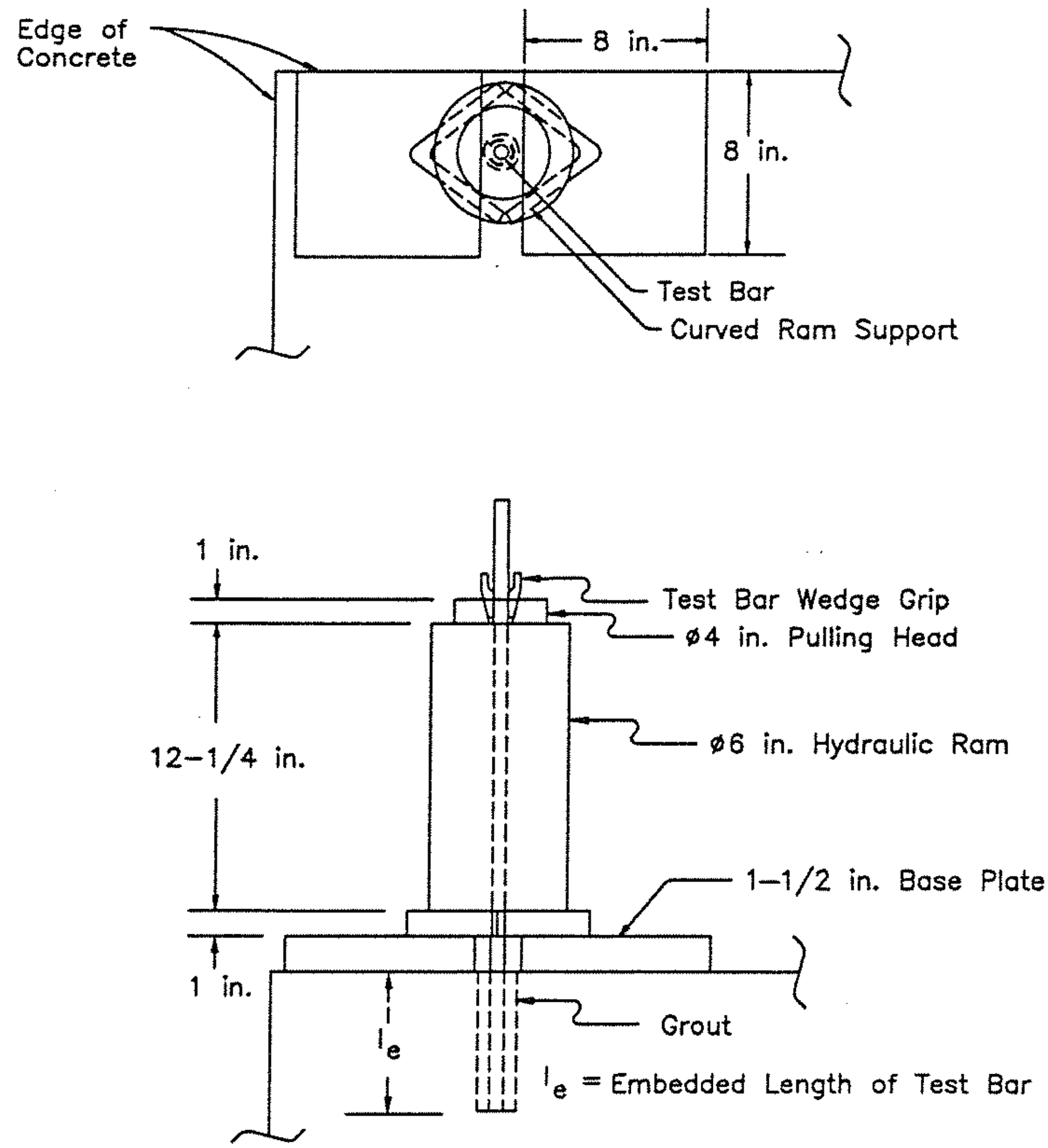

Fig. 5.1 Field Test Setup Evaluated in this Study. Note: This procedure is not recommended.

APPENDIX A – PROPOSED STANDARD TEST METHOD FOR BOND STRENGTH PROVIDED BY GROUT TO REINFORCING BARS ANCHORED IN CONCRETE

1. Scope

1.1 This test method describes procedures to establish the bond strength provided by grouting materials anchoring single reinforcing bars in concrete.

1.2 The test method is intended for use in establishing the Strength Class of grout anchoring reinforcement that is installed perpendicular to a plane surface of a structural member. Separate evaluations must be made for bars installed horizontally and vertically. The strengths obtained with the test methods may be conservatively applied to grouted bars that are not installed perpendicular to a plane surface, if the test results are considered to apply based on the minimum cover of the reinforcing bars.

1.3 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices in determining applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ***ASTM Standards*:**

A 615 Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement

C 192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

E 4 Practices for Load Verification of Testing Machines

E 171 Specification for Standard Atmospheres for Conditioning and Testing Materials

E 575 Practice for Reporting Data from Structural Tests of Building Constructions, Elements, Connections, and Assemblies

3. Terminology

3.1 *Description of Terms Specific to This Standard:*

3.1.1 *bond strength*, T_e – maximum measured load in a tensile test of a grouted reinforcing bar

3.1.2 *cover* – minimum distance between the surface of a grouted reinforcing bar and an adjacent parallel concrete surface

3.1.3 *embedment length,* ℓ_e – the distance from the surface of the concrete test specimen to the installed end of the grouted reinforcing bar

3.1.4 *hole diameter* – diameter of the drilled hole in which the grouted reinforcing bar is inserted and anchored

3.1.5 *side cover* – minimum distance from the center of a grouted reinforcing bar to a parallel surface of concrete measured in a direction perpendicular to the direction in which cover is measured

3.1.6 *Strength Class* – A category of grout based on the bond strength it provides for embedded reinforcement, when tested and evaluated in accordance with this standard. Three Strength Classes are defined in section 9.1.

3.2 *Symbols:*

A_b = Area of an individual bar, sq. in.

d_b = Nominal diameter of reinforcing bar, in.

f'_c = Compressive strength of concrete, psi

$\sqrt{f'_c}$ = Square root of concrete compressive strength, psi

f_s = Tensile stress in reinforcement, psi

γ = Factor obtained in evaluating grout strength = $T_e(avg)/\ell_e\sqrt{f'_c}$

4. Significance and Use

4.1 This test method is intended to establish the tensile bond strength provided by grouts anchoring single reinforcing bars in concrete. The strengths established by these test procedures are not representative of bond strengths provided by grouts to a group of closely clustered reinforcing bars.

4.2 The test method shall be followed to assure reproducibility of the test data.

5. Apparatus

5.1 ***Equipment*** – A schematic of a suitable testing system is shown in Fig. A.1. The loading system must be capable of measuring the forces to an accuracy within ±2 percent of the applied load, when calibrated in accordance with ASTM E 4. The test system shall have sufficient capacity to prevent yielding of its various components and shall insure that the applied tensile loads remain parallel to the axes of the reinforcing bars during testing.

5.2 ***Compression Reaction Plate*** – The compression reaction plate shall be placed a minimum clear distance equal to ℓ_e measured from the center of the test bar to the edge of the reaction plate, for bars with $\ell_e = 9\ d_b$. The minimum clear distance shall be 0.75 ℓ_e for bars with $\ell_e = 15\ d_b$.

5.3 ***Bar Displacement Measurement*** – The displacement of the reinforcing bar shall be measured with respect to the loaded surface of the concrete using a suitable measurement device. Dial gauges having the smallest division of not more than 0.001 in. or linear variable differential transformers (LVDTs) with equal or superior accuracy are examples of satisfactory devices.

6. Test Specimen

6.1 ***Concrete Block*** – The test specimen shall consist of a block of concrete 24 in. long by 18 to 27 in. wide by 24 in. high. Specimens with a width of 18 in. can accommodate one test bar. Specimens with a width of 27 in. can accommodate two test bars. A typical test specimen is illustrated in Fig. A.2. The concrete block shall be fabricated using concrete designed to produce a strength at the time of test between 4500 and 5500 psi. The specimen shall be cast in two layers, each of approximately 12 in. in depth. Each layer shall be adequately consolidated with an internal vibrator to insure the removal of entrapped air.

6.2 ***Hole Preparation*** – A hole with a diameter of $d_b + 1/4$ in. $\pm$ $1/16$ in., or other diameter as recommended by the manufacturer or needed for evaluation, shall be drilled in the concrete block to a depth ℓ_e from the top surface or side surface of the block for vertical or horizontal bar installation, as required. For establishing the Strength Class of a grout, the cover shall be 3 in. and the side cover measured to the center of the bar shall be 9 in.

Prior to installation of the grouted reinforcing bar, the hole shall be cleaned by vacuuming the bottom of the hole using a suitably sized nozzle to fit in the hole. The inside of the hole shall then be thoroughly scrubbed with a fiber bottle brush, followed by a blast of compressed air to remove all traces of loose material.

6.3 ***Grout and Bar Installation*** – The grouted reinforcing bar shall be installed in accordance with the manufacturer's recommended procedures and tools or, where specific deviation is justified, in accordance with good field practice.

7. Conditioning

7.1 ***Specimen Conditioning and Curing*** – The concrete block shall be cured in the forms using a curing compound and/or a plastic membrane to prevent rapid evaporation of water until the concrete has attained a strength of at least 3000 psi. The formwork may then be removed to allow the surface of the concrete to dry prior to the time of test. Following bar installation, adequate curing time shall be provided for the grout in accordance with the manufacturer's recommended procedures. Specimen conditioning and curing shall be such that the concrete strength shall be between 4500 and 5500 psi at the time of test, unless another concrete strength is required. Standard concrete cylinders shall be prepared in accordance with ASTM C 192 using a representative sample of the concrete used to make the concrete block. The concrete cylinders shall be cured adjacent to and in the same manner as the concrete block. A minimum of two test cylinders are required.

7.2 ***Specimen Moisture and Temperature*** – If moisture and temperature conditions can affect the performance of the grout, these parameters shall be kept as constant as possible for a given series of tests.

8. Tensile Bond Tests

8.1 ***Number of Tests*** – To determine the Strength Class of a grout for a single bar orientation, a minimum of six bar installations are required – three each for embedment lengths $\ell_e = 9\ d_b$ and $\ell_e = 15\ d_b$.

8.2 ***Test Bar Size*** – The standard bar size for qualifying a grout as a Strength Class A grout or Strength Class B grout shall be an ASTM A 615 No. 5 bar. Special Strength Class grouts may be qualified with any size reinforcement; however, the qualification is limited to the bar size tested.

8.3 ***Bar Orientation*** – Separate qualifications are required for grouts meant to anchor vertical and horizontal bars. Horizontal bar installations must be made in the upper portion of the concrete block.

8.4 ***Test Procedure*** – A tensile load shall be applied to the test bar, as illustrated in Fig. A.1. A loading rate of 10 to 50 percent of the anticipated grout capacity per minute should be used, except a minimum total test time of 2 min. shall be required. At least 10 intermediate displacement and load readings should be taken in addition to the initial and ultimate load.

8.5 ***Long-term Tests*** – If required for a specific application, load may be maintained for a longer period, such as 24 hours, to determine the long-term strength of the reinforcing bar-grout installation.

9. Grout Strength Class

9.1 ***Establishing Grout Strength Class*** – Following completion of a minimum of three tests each for embedment lengths of $9\ d_b$ and $15\ d_b$, the factor γ shall be calculated separately based on average bond strengths, $T_e(avg)$, for each embedment length, in accordance with Eq. A.1.

$$\gamma = \frac{T_e(avg)}{\ell_e\sqrt{f'_c}} \tag{A.1}$$

The grout Strength Class shall be established based on the smaller of the two values of $\gamma = \gamma_{min}$. Strength Classes A and B shall be established based on tests of grouted No. 5 bars. If γ_{min} is $\geq$ 30, the grout is qualified as a Strength Class A grout. If γ_{min} is < 30, but > 21, the grout is qualified as a Strength Class B grout. Any grout, anchoring a bar of any size, can be qualified as a Special Strength Class grout, for which the strength is characterized by γ_{min}.

10. Report

10.1 The report shall the include the applicable information listed in ASTM Practice E 575, and shall specifically include the following:

10.1.1 Dates of test and date of report.

10.1.2 Test sponsor and test agency.

10.1.3 Identification of the bar size tested.

10.1.4 Identification of the grout tested: manufacturer, trade name, generic description, and installation procedures.

10.1.5 Description of the installation and testing procedure, if these deviated in any way from this standard.

10.1.6 Description of the concrete used for the concrete block, including mix design of the concrete, aggregate type, 28-day compressive strength, compressive strength at the time of test (average of a minimum of two cylinders), and age of the concrete at the time of test.

10.1.7 Age of the grout at the time of test.

10.1.8 Description of the procedure, tools, and materials used to install the grout and reinforcing bar system and any deviation from those recommended.

10.1.9 Moisture condition at time of test.

10.1.10 Embedment length and bar orientation of the installed reinforcement, in in.

10.1.11 Description of test method and loading procedure used and actual rate of loading.

10.1.12 Number of replicate specimens tested.

10.1.13 Mean and individual maximum load values, in pounds, for each grout reinforcement installation.

10.1.14 The value of γ and the grout Strength Class for which the grout is qualified.

10.1.15 Photographs, sketches, or word descriptions, or combination thereof of the failure modes observed.

10.1.16 Summary of findings, and

10.1.17 Listing of observers of tests and signatures of responsible persons.

11. Precision and Bias

11.1 No statement is made on the precision or bias of this test method, since the test results indicate only whether there is conformance to given criteria and since no generally accepted method for determining precision and bias of this test method is currently available. General guidelines provided herein for the specimens, instrumentation, and procedures make the results intractable to calculation of meaningful values by statistical analysis for precision and bias at this time.

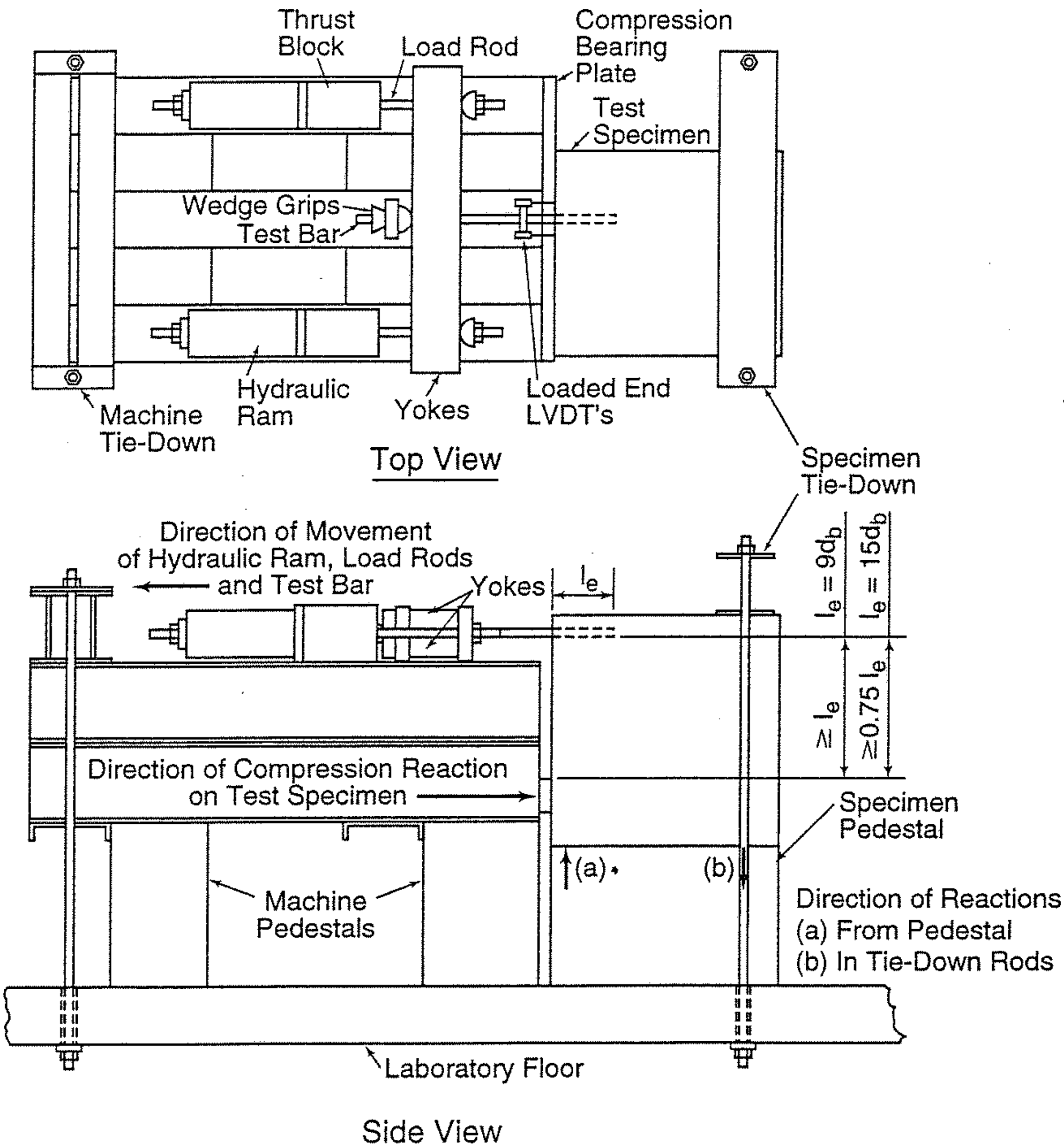

Fig. A.1 Schematic of Test System

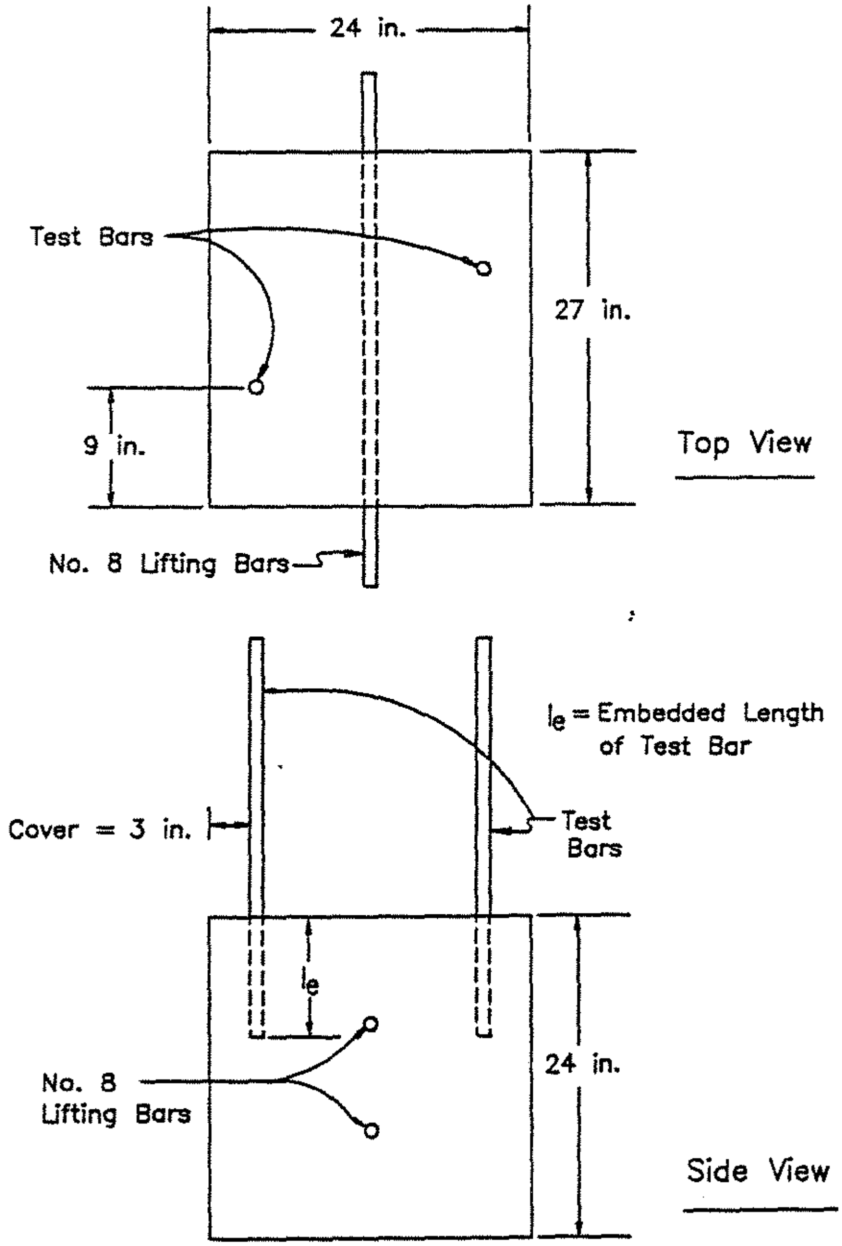

Fig. A.2a Typical Test Specimen with Vertical Bar Installation

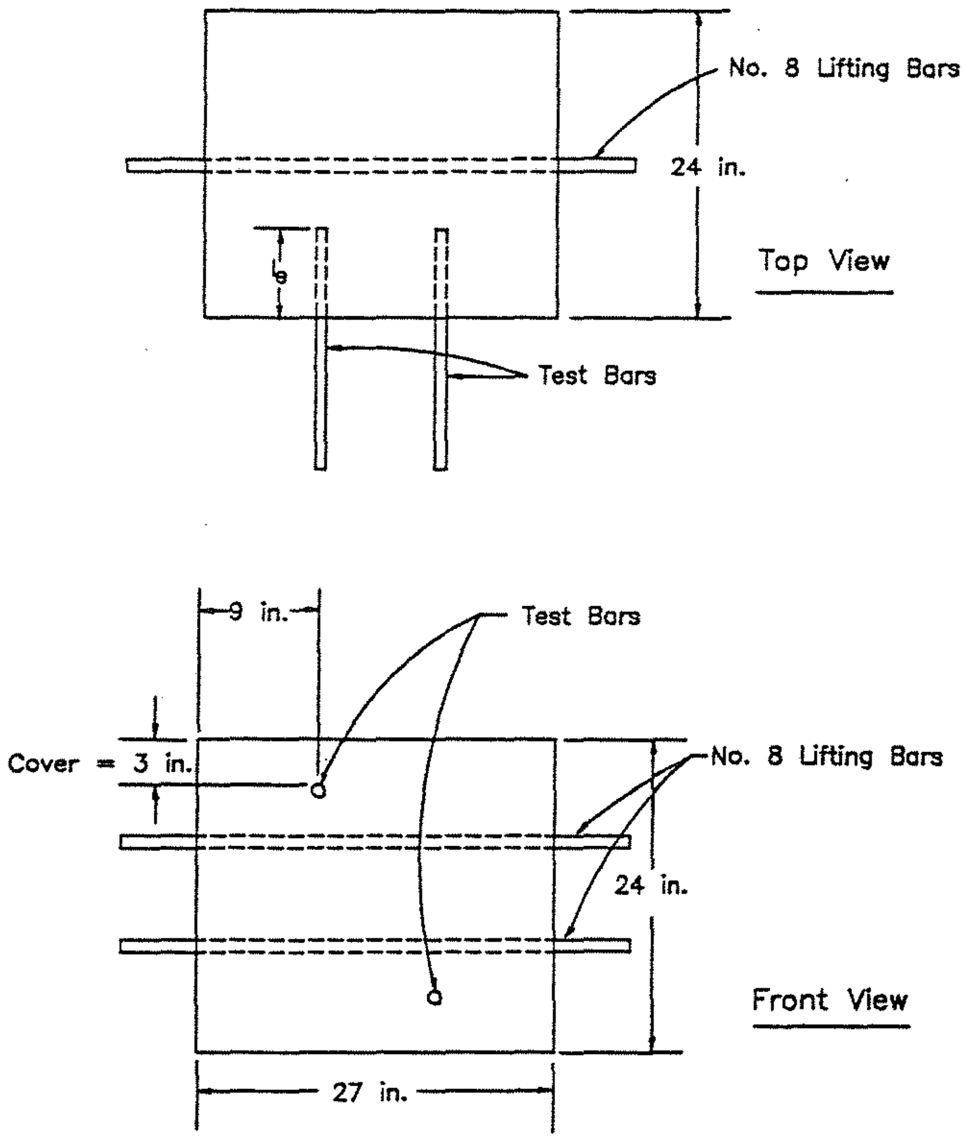

Fig. A.2b Typical Test Specimen with Horizontal Bar Installation

Appendix B: Slopes, Intercepts, Coefficients of Determination, and Test Groups for Best Fit Lines in Figures Comparing Modified Bond Strengths to Embedment Lengths

Figure		Slope	Y Inter.	r^2	Test Groups
3.1	C-M-CIP	2.109	2.612	0.930	15-17
	C&S-E-CIP	2.361	−0.021	0.953	15-17
	C&S-E-TCB	2.157	0.954	0.946	15-17
	C-E-TCA	1.858	−0.233	0.869	11,15-17,22
3.2	M-CIP	3.015	0.434	0.978	8-10,12-14
	E-CIP	2.472	2.113	0.940	8-10,12-14
	E-TCB	2.394	2.323	0.900	8-10,12-14
	E-TCA	2.191	−1.850	0.872	8-10,12-14
3.3	C-E-CIP	2.481	−0.016	0.984	15-17
	S-E-CIP	2.242	−0.025	0.956	15-17
	C-E-TCB	2.177	1.195	0.946	15-17
	S-E-TCB	2.137	0.715	0.952	15-17
3.4	No. 8 Bars				
	M-CIP	3.015	0.434	0.978	8-10,12-14
	E-CIP	2.472	2.113	0.940	8-10,12-14
	E-TCB	2.394	3.108	0.900	8-10,12-14
	E-TCA	2.191	−1.850	0.872	8-10,12-14
	No. 5 Bars				
	M-CIP	2.109	2.612	0.930	15-17
	E-CIP	2.481	−0.018	0.984	15-17
	E-TCB	2.021	2.889	0.880	15-17,22
	E-TCA	1.858	−0.233	0.869	11,15-17,22
3.5	3 in. Cover				
	M-CIP	2.109	2.612	0.930	15-17
	E-CIP	2.481	−0.018	0.984	15-17
	E-TCB	2.021	2.889	0.880	15-17,22
	E-TCA	1.858	−0.233	0.869	11,15-17,22
	1.5 in. Cover				
	M-CIP	2.433	−1.498	0.944	19
	E-CIP	2.225	−1.281	0.994	19
	E-TCB	1.956	1.222	0.939	19,22
	E-TCA	1.505	−0.952	0.844	19,22
3.6	Groups 18 & 20				
	E-CPA-T	2.443	3.648	0.849	18,20
	E-NSA-T	2.698	−4.585	0.967	18,20
	E-TCA-T	1.987	1.467	0.887	18,20

Appendix B, Continued

Figure		Slope	Y Inter.	r^2	Test Groups
	Group 24				
	E-CPA-T	2.790	0.238	0.934	24
	E-NSA-T	2.378	−0.027	0.962	24
	E-TCA-T	2.842	−7.459	0.919	24
3.7	Groups 18 & 20				
	E-NSA-B	3.443	−9.153	0.997	18,20
	E-TCA-B	2.267	−1.199	0.961	18,20
	Group 24				
	E-NSA-B	2.482	0.274	0.988	24
	E-TCA-B	2.394	−0.952	0.958	24
3.8	No. 8 Bars				
	E-CPA-T	2.559	2.511	0.877	18,20,24
	E-CIP-T	2.280	4.910	0.908	18,20
	E-NSA-T	2.538	−2.306	0.944	18,24
	E-TCA-T	2.277	−1.525	0.876	18,20,24
	No. 5 Bars				
	E-CPA-T	−0.926	12.650	0.818	21
	E-CIP-T	2.213	0.893	0.985	21
	E-TCA-T	1.218	4.244	0.936	21
3.9	No. 8 Bars				
	E-CPA-B	2.522	5.552	0.952	18,20
	E-CIP-B	2.438	5.725	0.879	18,20
	E-NSA-B	2.771	−2.905	0.961	18,24
	E-TCA-B	2.317	−1.056	0.949	18,20,24
	No. 5 Bars				
	E-CPA-B	−0.370	9.100	0.838	21
	E-CIP-B	2.424	0.070	0.990	21
	E-TCA-B	1.315	3.524	0.842	21
3.10	E-CPA-B	2.522	5.552	0.952	18,20
	E-CIP-B	2.438	5.725	0.879	18,20
	E-NSA-B	2.771	−2.905	0.961	18,24
	E-TCA-B	2.317	−1.056	0.949	18,20,24
	E-CPA-T	2.559	2.511	0.877	18,20,24
	E-CIP-T	2.280	4.910	0.908	18,20
	E-NSA-T	2.538	−2.306	0.944	18,24
	E-TCA-T	2.277	−1.525	0.876	18,20,24
3.11	E-CPA-B	−0.370	9.100	0.838	21
	E-CIP-B	2.424	0.070	0.990	21

Appendix B, Continued

Figure		Slope	Y Inter.	r^2	Test Groups
	E-TCA-B	1.315	3.524	0.842	21
	E-CPA-T	−0.926	12.650	0.818	21
	E-CIP-T	2.213	0.893	0.985	21
	E-TCA-T	1.218	4.244	0.936	21
3.12,4.2	E-CPA-T	2.559	2.511	0.877	18,20,24
	E-CIP-T	2.280	4.910	0.908	18,20
	E-NSA-T	2.538	−2.306	0.944	18,24
	E-TCA-T	2.277	−1.525	0.876	18,20,24
	E-CIP-V	2.473	2.113	0.940	8-10,12-14
	E-TCB-V	2.394	2.323	0.900	8-10,12-14
	E-TCA-V	2.191	−1.850	0.872	8-10,12-14
3.13,4.1	E-CPA-T	−0.370	9.100	0.838	21
	E-CIP-T	2.424	0.070	0.990	21
	E-TCA-T	1.315	3.524	0.842	21
	E-CIP-V	2.453	0.348	0.976	1-6,15-17
	E-TCB-V	2.021	2.889	0.880	15-17,22
	E-TCA-V	1.858	−0.233	0.869	11,15-17,22
3.14	Slope 1:3				
	E-NSA	1.475	10.707	1.000	24
	E-CPA	−0.271	9.928	0.561	24
	Slope 1:6				
	E-TCB	2.821	−3.996	0.961	24
	E-NSA	4.507	−19.654	0.981	24
	E-CPA	0.715	2.711	0.780	24
5.1	Field Tests				
	E-CPA	−0.512	11.727	0.987	F1(18),F3(20)
	E-TCB	1.230	13.851	0.598	F1(18),F3(20)
	E-TCA	0.820	10.295	0.152	F1(18),F3(20)
	E-NSA	1.230	13.956	0.755	F1(18),F3(20)
	Beam-end Tests				
	E-CPA	−0.926	12.650	0.818	21
	E-TCB	2.021	2.889	0.880	15-17,22
	E-TCA	1.858	−0.233	0.869	11,15-17,22

APPENDIX C - NOTATION

A	=	Air cleaning method
A_b	=	Area of an individual bar, sq. in.
B	=	Bottom-cast horizontal bar
BA	=	Brush with air cleaning method
BW	=	Brush with water cleaning method
C	=	C bar pattern
CIP	=	Cast-in-place
Cone	=	Cone failure mode
CPA	=	Capsule A (see Table 2.4)
CPB	=	Capsule B (see Table 2.4)
E	=	Epoxy-coated
f'_c	=	Compressive strength of concrete, psi
$\sqrt{f'_c}$	=	Square root of concrete compressive strength, psi
f_s	=	Tensile stress in reinforcement, psi
H	=	Horizontal bar
H_o	=	Null hypothesis
H_1	=	Alternate hypothesis
IGC	=	Failure at interface between grout and concrete
IGR	=	Failure at interface between grout and reinforcement
ℓ_e	=	Embedded length of grouted reinforcement, in.
M	=	Mill scale (uncoated)
NSA	=	Nonshrink grout A (see Table 2.4)
NSB	=	Nonshrink grout B (see Table 2.4)
NTR	=	No tensile reinforcement
Pullout	=	Pullout failure

S	=	S bar pattern
S	=	Splitting failure
s_1, s_2	=	Measured standard derivations
T	=	Top-cast horizontal bar
T	=	Tensile failure
T_e	=	Tensile force in grouted reinforcement, pounds
T_n	=	Nominal tensile force in grouted reinforcement, pounds
TCA	=	Two-component grout A (see Table 2.4)
TCB	=	Two-component grout B (see Table 2.4)
T	=	Top-cast horizontal bar
V	=	Vacuum drilled
V	=	Vertical bar
$\bar{X}_1$, $\bar{X}_2$	=	Measured mean strengths
α	=	Level of significance
γ	=	Factor obtained in evaluating grout strength = $T_e(avg)/\ell_e\sqrt{f'_c}$
μ_1, μ_2	=	Population mean strengths
ϕ	=	Strength reduction factor